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FLIGHT TESTS OF SEVERAL EXHAUST-GAS-TO-AIR HEAT EXCHANGERS

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SUMMARY

Thirteen exhaust-gas-to-air heat exchangers have been tested in flight to determine the practicability of the use of such heat exchangers in the thermal ice-prevention systems on aircraft. The results, given in the form of performance charts, show that exhaust-air heat exchangers constitute an excellent source of heated air for aircraft ice prevention and that they can be constructed to withstand the thermal and vibrational stresses to which they are subjected when installed in an airplane exhaust system. A comparison of the performance characteristics of the four types of exhaust-air heat exchangers tested in this investigation shows that no particular type is distinctly superior in all respects to the other types.

INTRODUCTION

Early in 1942 when consideration was first being given to the use of heated air as the working fluid in aircraft thermal ice-prevention systems, one of the chief difficulties encountered was the lack of an adequate source of heated air. The air-conditioning and petroleum industries had made extensive use of heat exchangers as sources of heated air, but these heat exchangers were heavy, bulky, and generally unsuitable for use on aircraft. Unit combustion heaters and intensifier tubes were being used on aircraft to supply heated air for cabin-heating systems; however, both of these heat exchangers proved inadequate to meet the demands of a thermal ice-prevention system. Thus, it became evident that in order to develop a successful thermal ice-prevention system using heated air as the working fluid it would also be necessary to develop an adequate source of heated air.

Preliminary investigations showed that a heat exchanger which would efficiently use the heat in the exhaust gases was the most promising source of heated air for use on aircraft and that a satisfactory heat exchanger should have the following characteristics:

1. The rate of heat transfer from gas to air must satisfy the requirements of the ice-prevention system.

2. The air-side flow resistance must be sufficiently low that the dynamic pressure in flight will suffice as a pump for the entire system.

3. The gas-side flow resistance should not cause excessive back pressures in the exhaust manifold.

4. The weight and over-all volume of the heat exchanger must be low.

5. The heat exchanger must be able to withstand the thermal and vibrational stresses to which it is subjected when installed in the exhaust system of an aircraft engine.

Prior to 1942 it was doubtful that such a heat exchanger could be manufactured. Therefore, the NACA in cooperation with the University of California and several aircraft and heat-exchanger manufacturers set out to determine whether or not suitable exhaust-air heat exchangers could be designed and constructed and, if so, whether they would stand up under service conditions in flight.

The general investigation was divided into three parts. The heat-exchanger manufacturers were encouraged to investigate the design and construction of several types of exhaust-air heat exchangers and to fabricate test units designed for use in a thermal ice-prevention system. The second part of the investigation, now being conducted at the University of California, includes the testing of exhaust-air heat exchangers in a ground-test stand and a detailed analysis of the heat-transfer and pressure phenomena encountered therein. The results of the completed portion of this part of the investigation are reported in references 1 to 13. The third part of the general investigation, conducted at AAL and reported herein, consists of the determination of the performance characteristics in flight of several exhaust-air heat exchangers. The primary purpose of this part of the investigation was to determine whether or not exhaust-air heat exchangers could be constructed with performance and service characteristics which would meet the demands of aircraft thermal ice-prevention systems.

NOTATION

The symbols used in this report are defined as follows:

A_s heat-transfer surface area, square feet

F/A engine fuel-air ratio

G mass velocity of fluid, pounds per hour per square foot

g gravitational constant, feet per hour per hour

ΔP pressure drop, inches of water

Q heat output, British thermal units per hour

t temperature, degree Fahrenheit

Vol over-all volume, cubic feet

v specific volume of fluid, cubic feet per pound

W fluid flow rate, pounds per hour

Wt weight of heat exchanger, pounds

<u>Subscripts</u>

a air side

g gas side

c carburetor

1 inlet

2 outlet

EQUIPMENT

The heat exchangers tested at AAL have been divided into four general groups according to their construction. These are as follows:

1. Flute type

2. Plate type

3. Tubular type

4. Pin or fin type

The details and materials of construction of the heat exchangers, together with diagrams showing the air-side shrouding used in the flight tests, are given in figures 1 to 39.

The three fluted heat exchangers shown in figures 1 to 9 were parallel-flow, all-primary-surface, cylindrical heat exchangers and consisted essentially of a series of trapezoidal ducts wrapped around a hollow cylindrical core. The air flowed through every other trapezoidal duct and the exhaust gas flowed through the central core and the remaining trapezoidal ducts.

Four plate-type heat exchangers were tested and are shown in figures 10 to 21. They were cross-flow, all-primary-surface heat exchangers approximately cubical in shape. These heat exchangers consisted of a number of alternating air and gas passages separated by thin plates. The air and gas passages of heat exchangers 35 and 48 were thin rectangular ducts. The separating plates were flat and the spacing of the passages was maintained by beads and dimples drawn into the flat plates. In heat exchangers 11 and 42 the plates were stamped to a wavy or corrugated pattern and were so assembled that the gas passages were tubes with a more-or-less diamond-shaped cross section. The air passages were wavy, thin, rectangular ducts formed by gaps left between adjacent rows of the gas passages.

The three tubular heat exchangers tested are shown in figures 22 to 30. These were cross-flow, all-primary-surface heat exchangers and were cylindrical in shape.

The tubes of heat exchanger 34 were flattened and the adjacent rows were staggered. Air flowed through the flattened tubes and the exhaust gases, bounded by the cylindrical shell, flowed across the flat-tube bundle. Heat exchangers 39 and 40 were round-tube bundles welded to the header plates. The air flowed across the tubes and the exhaust gases flowed through the tubes. On both of these heat exchangers iron abrasion plates, cut to match the tube pattern, were located at the inlet to the gas passages. The purpose of these plates was to protect the sharp upstream edges of the tubes from the abrasive action of the high-velocity gas stream.

Three pin- or fin-type heat exchangers are shown in figures 31 to 39. These were all cross-flow, extended-surface, cylindrical heat exchangers. The extended surfaces on heat exchanger 4 consisted or round, hollow pins resistance-welded to both sides of the cylindrical shell. The exhaust gas flowed through the cylinder and over the internal pins and the air flowed around the cylinder and over the external pins as shown in figure 33. On heat exchanger 7 the gas-side extended surfaces were continuous longitudinal fins running the length of the heat exchanger and extending radially from the cylindrical shell into the gas stream. The air-side heat-transfer surface consisted of discontinuous fins which extended outward from the shell as shown in figure 34. The air flowed around the cylinder and over the air fins as shown in figure 36. The extended surfaces of heat exchanger 28 consisted of channel sections the flanges of which had been serrated and bent to form the pattern shown in figure 37. The gas-side fins were spot-welded longitudinally along the inner surface of the shell and the air-side fins were wrapped radially around and spot-welded to the outer surface of the shell.

The heat exchangers were tested in flight on a North American O-47A airplane. This is a midwing monoplane powered with a Wright-Cyclone, single-row, nine-cylinder, radial, air-cooled engine with a piston displacement of 1820 cubic inches and rated at 835 horsepower at 2100 rpm at 3900 feet. The O-47A airplane is equipped with a cylindrical tail pipe which extends, along the right side of the fuselage, nearly to the wing trailing edge. One of the sections of the tail pipe was removed for the flight tests and was replaced by the heat-exchanger installations. Typical heat-exchanger installations are shown in figures 40 and 41.

Diagrams showing the air-side shrouding, used in the flight tests for each heat exchanger, are included in figures 3 to 39. In most cases, the shrouding was constructed from sheet aluminum although the shrouding for heat exchanger 34 was constructed from cold-rolled-steel sheet. Guide vanes were installed in the inlet headers to insure uniform air-flow distribution through the heat exchangers, and in one case (heat exchanger 42) the outlet header was also equipped with guide vanes. The straight shrouding, used in the isothermal tests, consisted merely of straight, rectangular, or circular ducts made from cold-rolled-steel sheet which were free from elbows, guide vanes, expansions, and contractions. Typical straight-shrouding installations are shown in figure 42. In the isothermal tests the source of air flow was a centrifugal fan the maximum capacity of which was approximately 2400 cubic feet per minute.

PROCEDURE AND MEASUREMENTS

During the flight tests level flight was maintained at a pressure altitude of 5000 feet and the engine speed and manifold pressure were held constant at 1800 rpm and 25 inches of mercury, respectively. The fuel-air ratio was adjusted in each test to obtain an indicated exhaust-gas temperature of 1600° F. The gas-flow rate at these engine conditions was about 3300 pounds per hour. The air-flow rate was varied in steps by means of a throttle valve located in the outlet-air duct. Three or four air-flow rates were used in each test. At each air-flow rate sufficient measurements were made to determine the exhaust-gas inlet temperature, gas-side static pressure drop, the air-flow rate, inlet- and outlet-air temperatures, and the air-side static pressure drop.

The ground tests were divided into two parts. The first part consisted of pumping air at room temperature through the air side of the heat exchanger and shrouding, as installed for flight tests. The guide vanes in the inlet header were adjusted until the air-flow distribution was practically uniform. Then the rate of air flow, as measured by a venturi meter and a sharp-edge orifice meter, was varied. At each value of air-flow rate the static pressures in the inlet- and outlet-air ducts were measured. The orifice meter was used to check the calibration of the venturi meter. In the second part of the ground tests the flight shrouding was replaced by the straight shrouding and the static pressures were measured ahead of and behind the heat exchanger at several air-flow rates.

The measurements taken in the preceding tests are briefly described as follows:

Air-flow rate.- With one exception the air-flow rates were determined by means of venturi meters. These meters were calibrated against a 4-inch, sharp-edge orifice meter the calibration of which had been checked by velocity surveys. During the flight tests on heat exchanger 11, the air-flow rate was determined by means of a simplified pitot-tube survey which is described in reference 14. This method had been checked with a venturi meter and was found satisfactory.

Inlet-air temperature.- Preliminary tests in which the inlet-air scoop was located aft of the cowl skirt indicated that some of the warm, low-velocity air emerging from the cowl skirt was entering the intake scoop. Therefore, in the tests reported herein, the inlet-air duct was extended forward to the front of the cowl so that only air at the free-stream temperature entered the duct. Two unshielded iron-constantan thermocouples located in the inlet-air duct about one foot forward of the heat exchanger consistently indicated that the entering air temperature was within 2° or 3° F of the free-stream temperature.

Outlet-air temperature.- Five unshielded iron-constantan thermocouples, spaced across a diameter of the outlet-air duct, located from three to five duct diameters downstream from the heat exchanger outlet were used to determine the outlet-air temperature. In most of the tests the outlet-air duct was insulated with a quarter-inch layer of asbestos lagging which extended from the heat exchanger outlet to a point about ten duct diameters downstream. When this insulation was used, the temperature was practically constant over the cross section in which the thermocouples were located. The mean deviation in indicated temperature was less than ±3 percent. In tests on heat exchangers 4, 11, 28, and 29, however, the outlet-air duct was not insulated. In these tests the temperature distribution in the duct varied and, since the velocity distribution in the duct was not known, it was impossible to obtain a true average temperature, Therefore, the arithmetic average temperature was used and the values of heat output shown for these heat exchangers are more uncertain than are the values given for the other heat exchangers.

Exhaust-gas-flow rate.- The exhaust-gas-flow rate was determined in flight by two independent methods. In one method the carburetor air-flow rate was measured by means of a venturi meter located just forward of the carburetor air-intake scoop, the fuel-air ratio was measured with a Cambridge analyzer, and the gas-flow rate was calculated from the carburetor air-flow rate and the fuel-air ratio. In the other method the exhaust-gas-flow rate was measured directly by means of a stainless-steel venturi meter located in the exhaust tail pipe. This venturi meter had been calibrated in the heat-exchanger test stand at the University of California with an inlet-gas temperature of 1600° F. The gas-flow rates determined by these two methods are compared in the following table:

Determination of Exhaust-Gas-Flow Rate

Engine, rpm	1800	1800	1900	2000
Manifold pressure, in. Hg.	22.4	25	25	28
$W_c + W_c F/A$, lb/hr	2730	3270	——	4400
Venturi meter, lb/hr	2940	3350	3560	4350

Pressure altitude: 5000 ft.
Inlet-gas temperature: 1600° F
W_c: carburetor air-flow rate
F/A: fuel-air ratio

From this table it is seen that, under the engine conditions at which the flight tests were made (1800 rpm and 25 in. H.P.), the exhaust-gas-flow rate was approximately 3300 pounds per hour. It is estimated that this value of gas-flow rate is accurate within ±5 percent.

Exhaust-gas temperature.- The inlet-gas temperatures given herein are not average entering-gas temperatures but are temperatures measured at the center of the tail pipe about 1 foot ahead of the heat exchangers and were used as reference temperatures. During the flight tests of most of the heat exchangers, a quadruple-shielded thermocouple of the type shown in figure 43 was used. The indicated temperature was not corrected for radiation error which, according to reference 15, was probably less than 2 percent. During the flight tests of heat exchangers 4, 11, 12, 28, and 29, the gas-temperature measurements were completely unsatisfactory but, since these tests were performed under the same conditions as were the tests of the other heat exchangers, it was assumed that the entering-gas temperatures were also the same.

Pressure drop.- Wall orifices and static tubes were used in conjunction with water manometers and airspeed meters to indicate the differences between static pressures ahead of and behind the heat exchangers. During the flight tests and also the isothermal tests with flight shrouding, the air-side differential pressures were measured between taps located approximately 1 foot upstream and six duct diameters downstream from the heat exchangers; the gas-side pressure taps were located about 1 foot upstream and six tail-pipe diameters downstream. During the isothermal tests with straight shrouding, the upstream pressure taps were located from 6 to 12 inches ahead of the heat exchanger, and the downstream taps were located sufficiently far aft of the heat exchanger to be in a region of stable flow. The air-side pressure drop measured in tests on heat exchanger 4 has been corrected for the difference between the inlet- and outlet-duct areas. In all other tests, the upstream and downstream pressure taps were located in round ducts of the same diameter. The nonisothermal air-side friction pressure drop* for heat exchangers 10, 11, 12, 29, 34, 35, 42, and 48 was obtained by subtracting from the measured static pressure drop the value of the term $G^2(v_2-v_1)/5.2g$ (reference 16), which is the drop in static pressure due to the expansion of the air as it becomes heated. Values of nonisothermal air-side friction pressure drop are not given for the other heat exchangers because of the uncertainty involved in determining their air-side free area.

*Throughout this report the term "friction pressure drop" includes all of the skin-friction and mechanical expansion and contraction pressure losses occurring between the stations at which the measurements were made.

RESULTS AND DISCUSSION

The test data for each heat exchanger are given in the form of performance charts in figures 45 to 56. These charts include curves which show the variation of heat output and air-side pressure drop with air-flow rate and the variation of gas-side pressure drop with gas-flow rate. The values of heat output were calculated from the air-flow rate, temperature rise, and mean specific heat. The nonisothermal air-side static pressure drop measured in flight is given for each heat exchanger. The nonisothermal air-side friction pressure drop, which is the difference between the measured air-side static pressure drop and the change in static pressure due to the expansion of the air, is given for heat exchangers 10, 11, 12, 29, 34, 35, 42, and 48. The nonisothermal gas side pressure drop given in the charts is the static pressure drop measured in the flight tests. These values were not corrected for the change in static pressure due to the change in the specific volume of the gas because average gas temperatures were not measured. This correction is relatively unimportant, however, because on the gas side it is small in comparison to the friction pressure drop. All of the isothermal pressure-drop data consist of differences between static pressures measured ahead of and behind the heat exchangers. Since there is no change in specific volume in isothermal flow, the static pressure drop and friction pressure drop are identical. The isothermal air-side pressure drop with flight shrouding includes the duct losses between the pressure taps, but that with straight shrouding consists of only the heat exchanger losses because the pressure losses in the straight ducts were negligible.

The amount of heat required per heat exchanger by an aircraft thermal ice-prevention system depends upon many factors, principal among which are the size of the airplane, the number of engines on the airplane, the number of heat exchangers per engine, the airspeed and altitude for which the system is designed, and the number of purposes (such as wing protection, tail-surface protection, windshield protection, cabin heating, etc.) for which the system is designed. Therefore, a specific rate of heat output cannot be set as a criterion for a satisfactory heat exchanger. However, the rate of heat output per heat exchanger required by the thermal ice-prevention systems of the B-17F and

XB-24D airplanes (references 17 and 18) is approximately 200,000 Btu per hour under the following conditions:

Pressure altitude, 18,000 feet

Indicated airspeed, approximately 155 miles per hour

Air-flow rate, about 3000 pounds per hour

Gas-flow rate, approximately 4000 pounds per hour

Inlet-gas temperature, about 1600° F

Under these conditions the allowable air-side flow resistance of the heat-exchanger installation is approximately 6 inches of water. Previous experience has indicated that the flow resistance of the heat-exchanger installation should not exceed one-half of the dynamic pressure, which is about 12 inches of water at an indicated airspeed of 155 miles per hour.

The tests reported herein were made at a pressure altitude of 5000 feet; but, holding the other factors constant, the rate of heat transfer does not change appreciably with altitude, and the friction pressure drop at 18,000 feet is approximately twice that at 5000 feet. Therefore, in order to satisfy the preceding requirements at 18,000 feet, a heat exchanger when operating at 5000 feet, and at the same conditions of air- and gas-flow rate and gas temperature, should deliver approximately 200,000 Btu per hour with an air-side flow resistance of not more than 3 inches of water.

An examination of table I will show that only heat exchangers 35 and 48 fully satisfy the preceding requirements. Under the test conditions given therein these heat exchangers had heat outputs of 190,000 and 295,000 Btu per hour, respectively, and the nonisothermal air-friction pressure drops at 5000 feet were 2.5 and 2.8 inches of water, respectively. Although it is significant that both of these heat exchangers were of the flat-plate type, it should not be concluded that the other types are unsatisfactory. Most of the heat exchangers tested would satisfy the thermal requirements, and perhaps the preceding criterion for pressure drop is too conservative. It is known that three heat exchangers, practically the same as heat exchanger 7, were used to supply heated air for the thermal ice-prevention system of the B-17F airplane which has been successfully operated in icing conditions. In table I it is shown that all of the heat exchangers tested in this investigation, with the exceptions of heat exchangers 4, 10, 28, and 39, had heat-transfer characteristics which equaled or surpassed those of heat exchanger 7. It is also shown in table I that only heat exchangers 34 and 42 had excessive isothermal pressure losses with straight shrouding. Therefore, it is probable that heat exchangers 11, 12, 29, and 40, with properly designed air-side shrouding, would also have satisfactory air-side pressure-drop characteristics.

A definite criterion for the allowable increment of engine back pressure, added by an exhaust-air heat exchanger, has not been established. However, an increment of 2 inches of mercury, under cruising conditions at 18,000 feet, is not considered excessive. Therefore, an exhaust-gas pressure drop of about 1 inch of mercury, at 5000 feet and a gas-flow rate of 4000 pounds per hour, is probably satisfactory. (The exhaust-gas-flow rate from one of the engines on the B-17F airplane, or the XB-24D airplane, at cruising power is approx. 4000 lb/hr.) The data in figures 44 to 56 show that the gas-side pressure drop of most of the heat exchangers, at 5000 feet and a gas-flow rate of 4000 pounds per hour, was less than 1 inch of mercury. It is concluded, therefore, that the gas-side pressure-drop characteristics of most of the heat exchangers were satisfactory. It should be noted, however, that the increment of engine back pressure, due to a heat exchanger, under take-off and other high-power conditions will be from four to six times greater than at cruising conditions.

In general the weight and over-all volume of the heat exchangers tested in this investigation are considered satisfactory. These factors are not critical in the present stage of heat-exchanger development, and it is probable that as heat exchangers come into general use, smaller and lighter units will be developed without sacrificing heat output or serviceability.

The tests reported herein were completed in from 7 to 20 hours of flight per heat exchanger and were, therefore, of insufficient duration to justify conclusions regarding the service life of the heat exchangers. Heat exchanger 48 had buckled severely in less than 10 hours of testing, but this heat exchanger was made from cold-rolled-steel plates. An Inconel-plate heat exchanger stamped with the same dies has been tested for 18 hours without any signs of failure. The other plate-type heat exchangers were slightly distorted after testing but no indications of failure could be detected. Several heat-exchanger manufacturers have submitted the available service history of their units. A fluted heat exchanger exactly like heat exchanger 29 has been in continuous operation on a Pan-American Airways DC-3 airplane for more than 750 flying hours. A tubular heat exchanger exactly like heat exchanger 39 has been undergoing tests on an XB-24D airplane for more than 500 hours. About 1000 fluted heat exchangers similar to heat exchanger 10 have been in operation on PBY-5 airplanes for approximately 500 hours, and in that time only one failure, a crack in a welded joint holding the heat exchanger to the tail pipe, has been observed. A plate-type heat exchanger similar to heat exchanger 35 has been tested on an O-47B airplane for more than 25 hours without failure. Several semicircular flat-plate heat exchangers used for flame-damping research in a B-17F airplane have withstood 200 hours of testing without failure.

In view of the preceding facts of performance and service, there can be no doubt that exhaust-gas-to-air heat exchangers can be made to meet the requirements of the thermal ice-prevention systems of aircraft such as the B-17 and B-24 airplanes.

It was previously noted that a B-17F airplane equipped with heat exchangers identical with heat exchanger 7 was flown successfully in icing conditions at Minneapolis during the winter of 1942. Other aircraft in which the thermal ice-prevention system included exhaust-air heat exchangers which were successfully operated in icing conditions include the XB-24D, XC-53A, and Lockheed 12A airplanes.

Because the heat exchangers tested in this investigation were so varied in shape and size and because of the high pressure losses involved in the air-side flight shrouding, any comparison of the performance characteristics has very little value. Nevertheless, an attempt at such a comparison has been made and is presented in table I. In this table the important physical and thermal characteristics are compared on the basis of constant gas-flow rate, air-flow rate, and inlet-gas temperature. The ratios of heat output to the weight, over-all volume, surface area, and isothermal pressure drop were calculated in an attempt to determine which type of heat exchanger had the best over-all characteristics. The isothermal friction pressure drop with straight shrouding was used in this comparison because the nonisothermal friction pressure drop included the shrouding losses. The data in table I indicate that the flat-plate heat exchangers had the best air-side pressure-drop characteristics and that the fluted heat exchangers, in which there is a hollow central core, had the best gas-side pressure-drop characteristics. At least one heat exchanger of each type tested, except the pin or fin type, delivered 7500 or more Btu per hour per pound of weight under the test conditions given in table I. This table also shows that the plate-type heat exchangers had slightly higher ratios of heat output per unit volume than the fluted, finned, and round-tube heat exchangers, and that the flat-tube heat exchanger was outstanding in this respect. It is further shown in table I that from the viewpoint of heat output per unit of surface area no particular type was outstanding. Thus the limited data contained in this report indicate that among the heat exchangers tested no one particular type was distinctly superior in all respects to the other types.

CONCLUSIONS

1. The data included in this report clearly indicate that exhaust-air heat exchangers can be designed and constructed with performance characteristics which satisfactorily meet the requirements of the thermal ice-prevention systems of aircraft such as the B-17 and B-24 airplanes.

2. Among the exhaust-air heat exchangers tested in this investigation no one particular type was distinctly superior to the others in all respects.

3. Further research is required to determine the best manner of reducing the nonuseful shrouding pressure losses in exhaust-air heat-exchanger installations.

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TABLE I.- COMPARISON OF HEAT-EXCHANGER PERFORMANCE

Heat exchanger	10	12	29	11	42	35	48	34	39	40	4	7	28
Figure number	2	5	8	17	20	11	14	23	26	29	32	35	38
Manufacturer	Solar	Aire-search	Aire-search	Trane	Trane	Briggs	AAL	AAL	Stewart-Warner	McQuay	Hanlon Wilson	Stewart-Warner	Hanlon Wilson
Type	flute[6]	flute[6]	flute[6]	wave plate	wave plate	flat plate	flat plate	flat tube	round tube	round tube	pin	fin	fin
W_g, gas-flow rate, lb/hr - - - - - -	3300	3300	3300	3300	3300	3300	3300	3300	3300	3300	3300	3300	3300
t_{g1}, inlet-gas temperature, $^{\circ}F$ - - -	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600
[1]ΔP_g (I), in. H_2O - - - - - - - - - - -	2.1	2.6	1.7	---	3.8	---	6.5	---	5.8	10.6	1.5	3.1	---
[2]ΔP_g (II), in. H_2O - - - - - - - - - -	0.3	0.5	0.4	1.7	0.8	---	---	---	1.2	---	0.3	0.5	0.5
W_a, air-flow rate, lb/hr - - - - - -	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
t_{a1}, inlet-air temperature, $^{\circ}F$ - - -	60	40	55	65	60	50	55	50	45	50	85	50	60
$Q \times 10^{-3}$, heat output, Btu/hr - - - -	125	230	180	250	190	190	295	315	150	180	40	185	55
[3]ΔP_a (I), in. H_2O - - - - - - - - - - -	6	14	5	5	9.5	2.5	2.8	13	---	---	---	---	---
[4]ΔP_a (II), in. H_2O - - - - - - - - - -	---	7.3	---	2	4.7	1.2	1.3	7	1.6	2.8	---	4.7	---
[5]ΔP_a (III), in. H_2O - - - - - - - - - -	1.2	1.6	1.2	1.6	4	0.4	0.3	3.1	---	0.8	0.8	---	1.4
ΔP_a (II)/ΔP_a (III) - - - - - - - - - -	---	4.6	---	1.2	1.2	3.0	5	2.3	---	3.5	---	---	---
Wt, weight of exchanger, lb - - - -	19.5	38	22.5	32	30	32	45	50	30	22	13	39	24.5
Vol, over-all volume, cu ft - - - -	0.5	0.96	0.71	0.52	0.35	0.55	0.78	0.47	0.46	0.55	0.4	0.65	0.45
A_g, surface area, sq ft - - - - - -	6.4	16.6	12.5	19	12	13.8	29	17	9.3	9.9	4.1	12.8	10
$Q/10^{-3}$/wt, Btu/(hr)(lb) - - - - - -	6.4	6.0	8	7.8	6.3	5.9	6.5	10.5	5	8.2	3.1	4.7	2.2
$Q/10^{-2}$/vol, Btu/(hr)(cu ft) - - - -	250	240	254	480	543	346	378	670	326	328	100	285	122
$Q/10^{-2}/A_g$, Btu/(hr)(sq ft) - - - -	19.5	13.9	14.4	13.1	15.8	13.8	10	18.5	16.1	18.2	9.8	14.5	5.5
$Q/10^{-2}/ P_a$(III), Btu/(hr)(in.H_2O) -	104	144	150	156	48	480	985	102	---	225	50	---	39

[1]ΔP_g (I) non-isothermal gas static pressure drop at 5000 feet altitude.

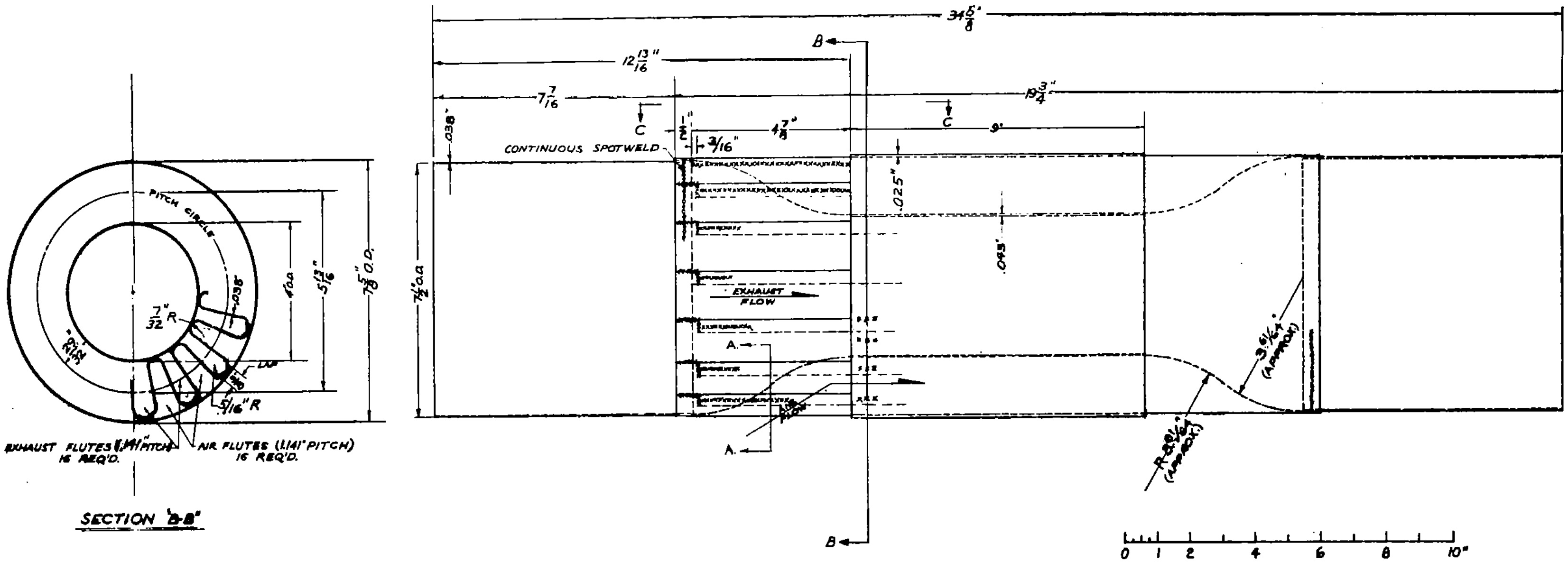
[2]ΔP_g (II) isothermal gas pressure drop with straight shrouding at sea level.

[3]ΔP_a (I) non-isothermal air friction pressure drop at 5000 feet altitude.

[4]ΔP_a (II) isothermal air pressure drop with flight shrouding at sea level.

[5]ΔP_a (III) isothermal air pressure drop with straight shrouding at sea level.

[6]Parallel-flow heat exchangers. All others were cross-flow.



SECTION "B-B"

SECTION "A-A"

	AIR SIDE	GAS SIDE
HEAT TRANSFER AREA	6.40 SQ FT	6.40 SQ FT
MINIMUM FREE AREA	0.11 SQ FT	0.19 SQ FT
WETTED PERIMETER	7.45 FT	7.60 FT
HEAT TRANSFER PERIMETER	5.45 FT	5.45 FT

FABRICATION - FLUTES LAPPED, SPOTWELDED & ENDS OF LAPS WELDED.
MATERIAL - STAINLESS STEEL
WEIGHT OF UNIT - $19\frac{1}{2}$ LBS

NOTES:

(A) WEIGHT OF Nº 1 WITHOUT SHROUD = 19.5 #
WEIGHT OF Nº 2 WITHOUT SHROUD = 17.5 #

ASSEMBLY MUST BE PRESSURE TIGHT.
TEST FOR LEAKS FROM GAS TO AIR SIDE AT 10 P.S.I. (MAX.)
SEAL LEAKS BY SPOTWELDING

NORMALIZE, PICKLE, & PASSIVATE AFTER ASSEMBLY.

FIGURE 1.- HEAT EXCHANGER 10 DESIGNED AND CONSTRUCTED BY SOLAR AIRCRAFT CO.

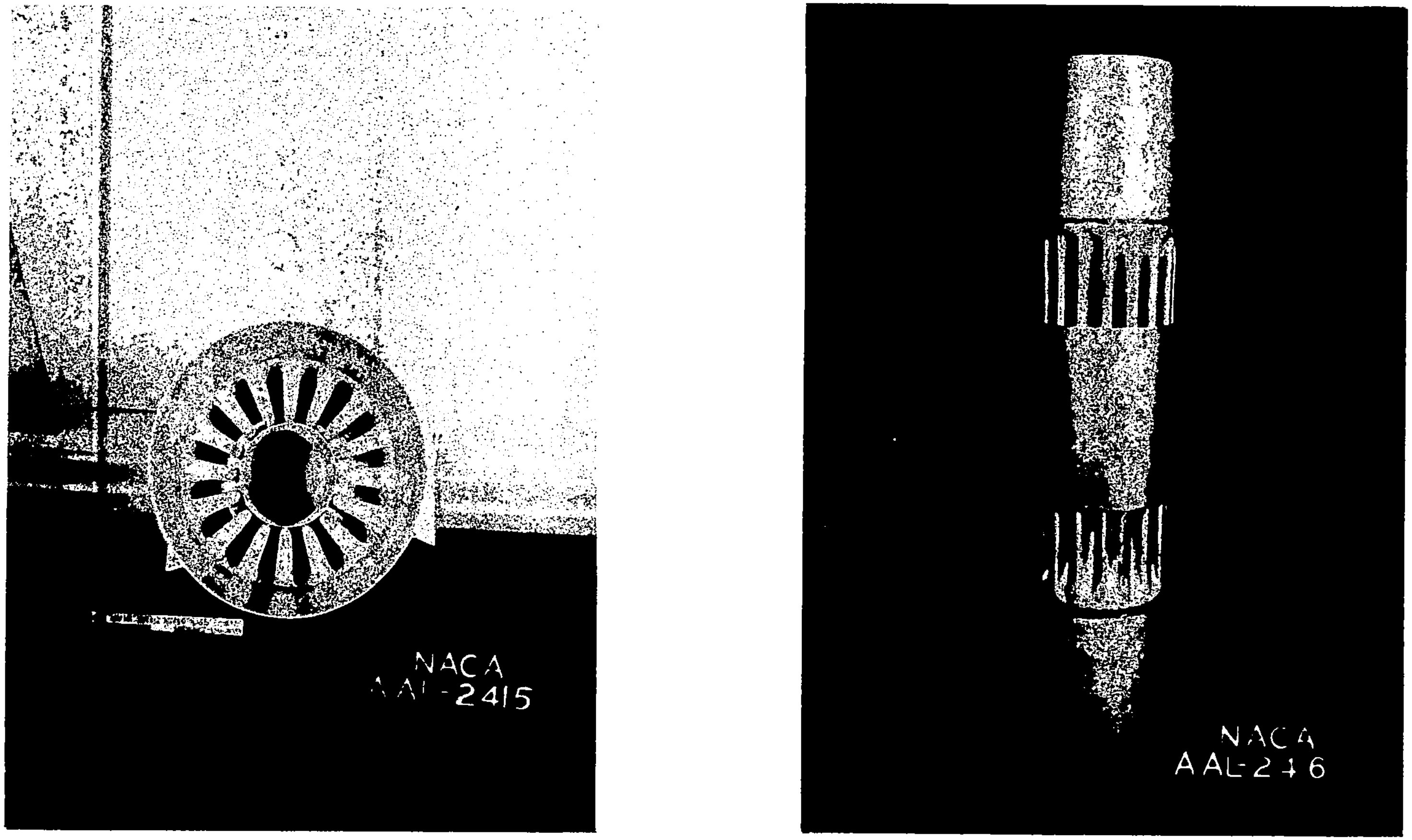


Figure 2.- Heat exchanger 10.

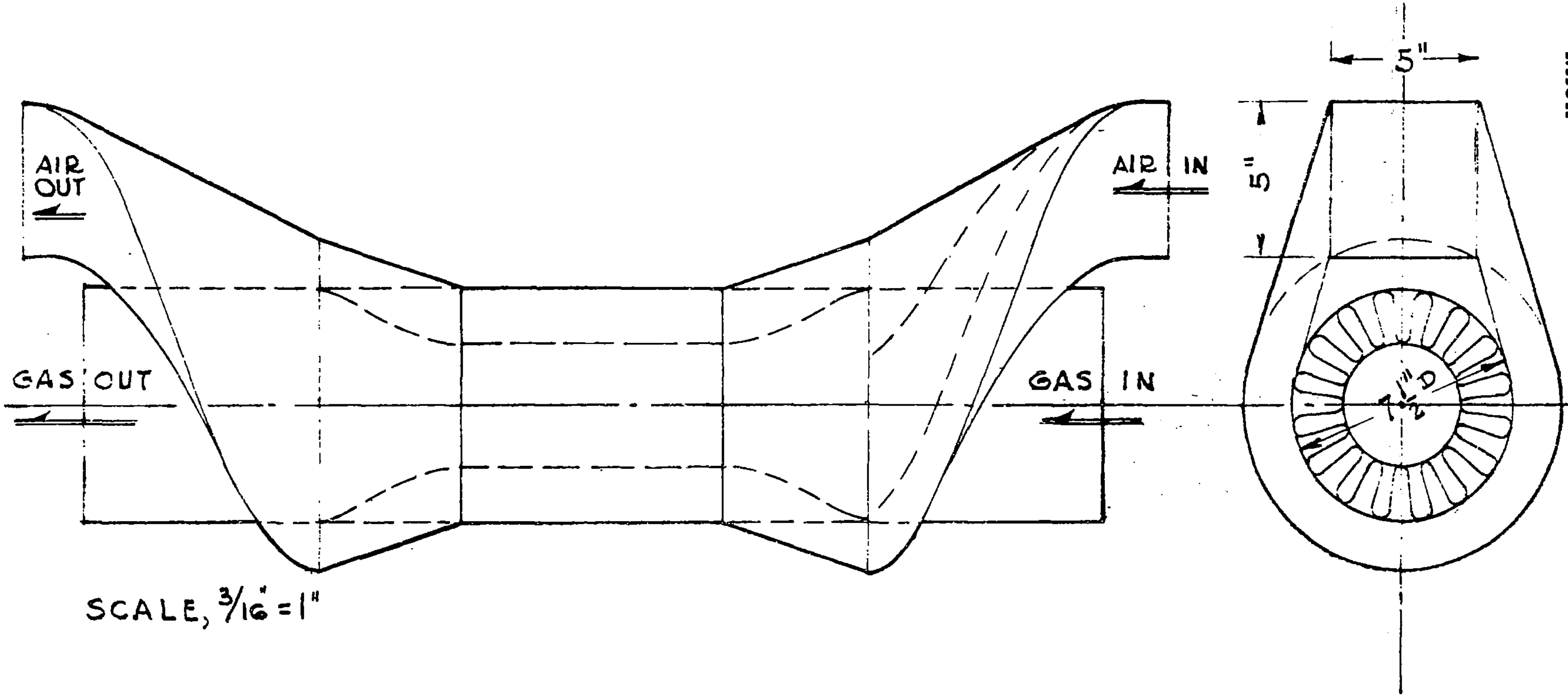
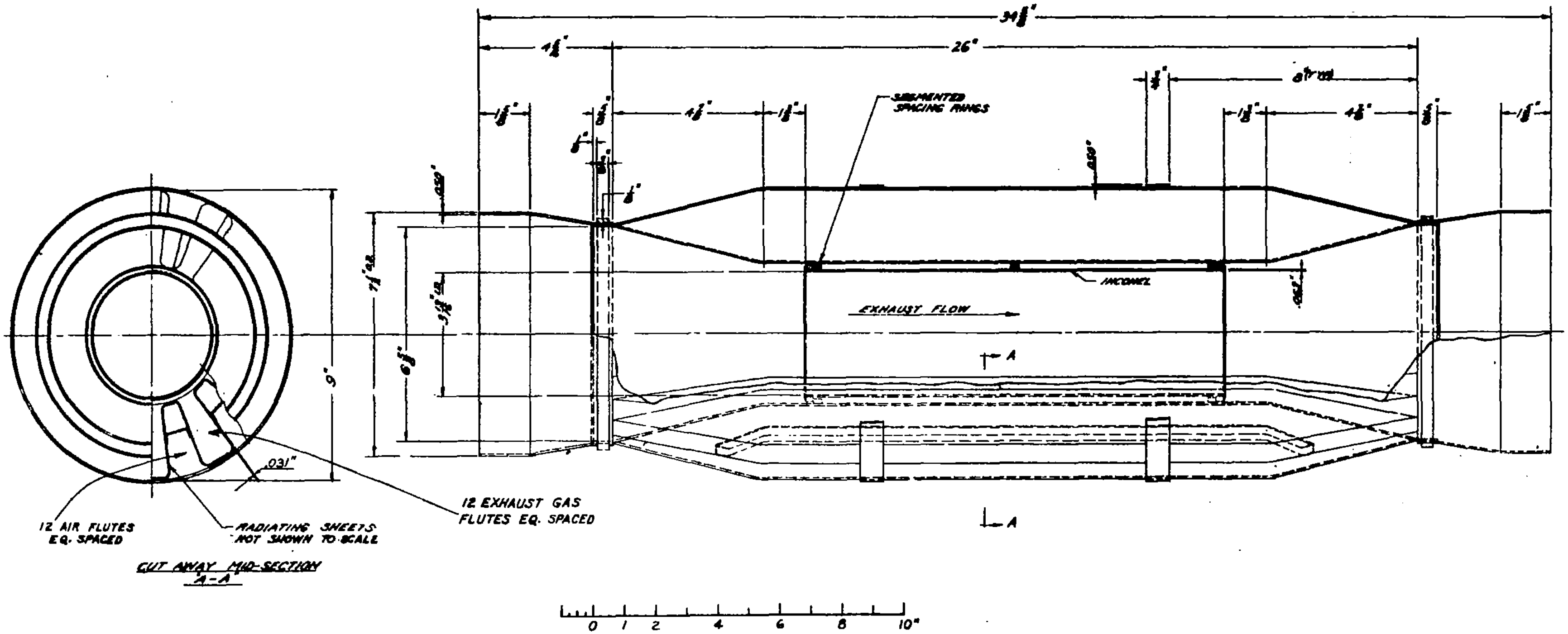


FIGURE 3.- DIAGRAM OF AIR-SIDE SHROUDING USED IN FLIGHT TESTS OF HEAT EXCHANGER 10

NACA

Fig. 3



	AIR SIDE	GAS SIDE
HEAT TRANSFER AREA	16.60 SQ FT	16.60 SQ FT
MINIMUM FREE AREA	0.175 SQ FT	0.24 SQ FT
WETTED PERIMETER	12.50 FT	12.0 FT
HEAT TRANSFER PERIMETER	10.0 FT	10.0 FT

FABRICATION - SEAM WELDED
MATERIALS - 18-8 STL. STEEL AND INCONEL
WEIGHT OF UNIT - 38¼ LBS

FIGURE 4.- HEAT EXCHANGER 12. DESIGNED AND CONSTRUCTED BY AIRESEARCH MFG. CO.

Figure 5.- Heat exchanger 12

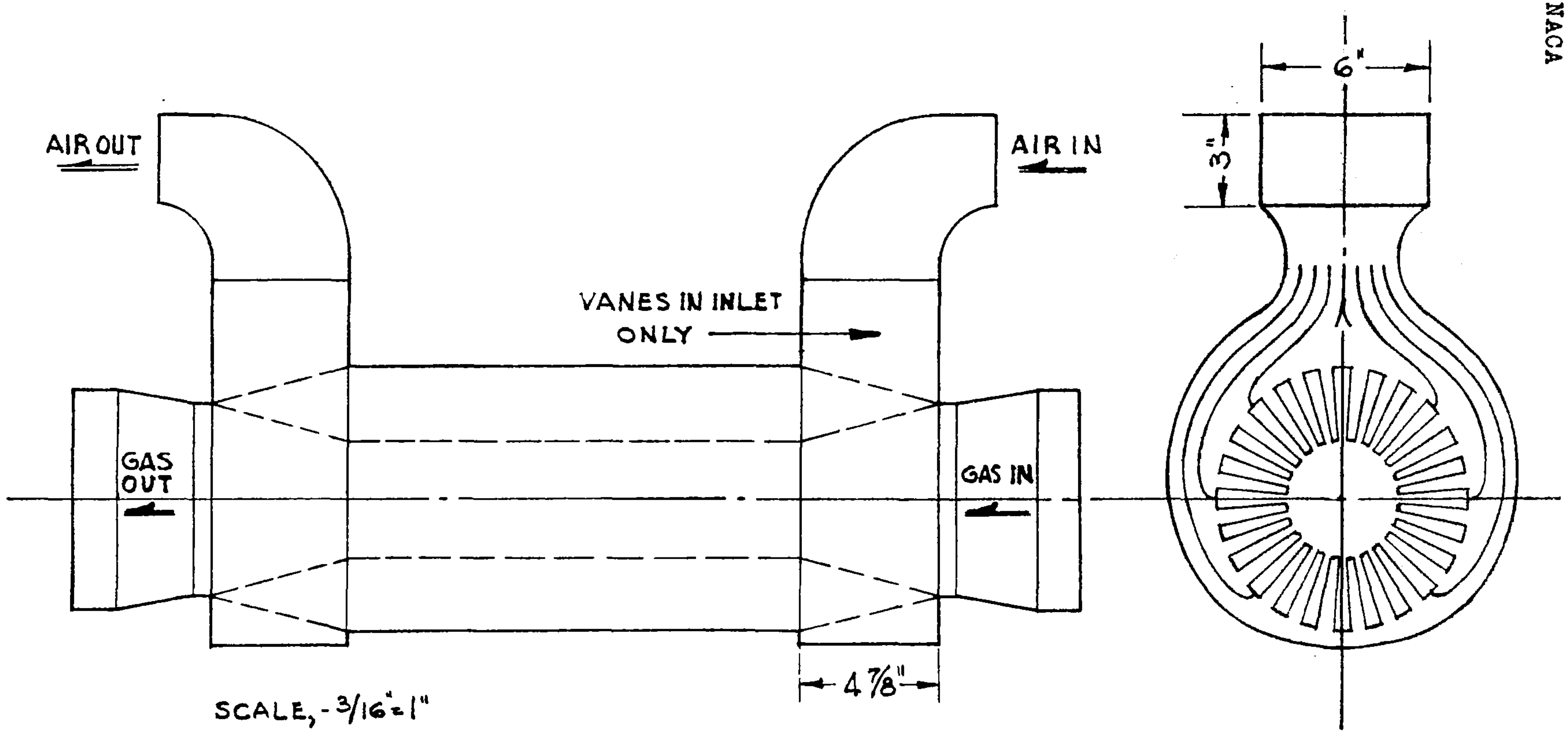
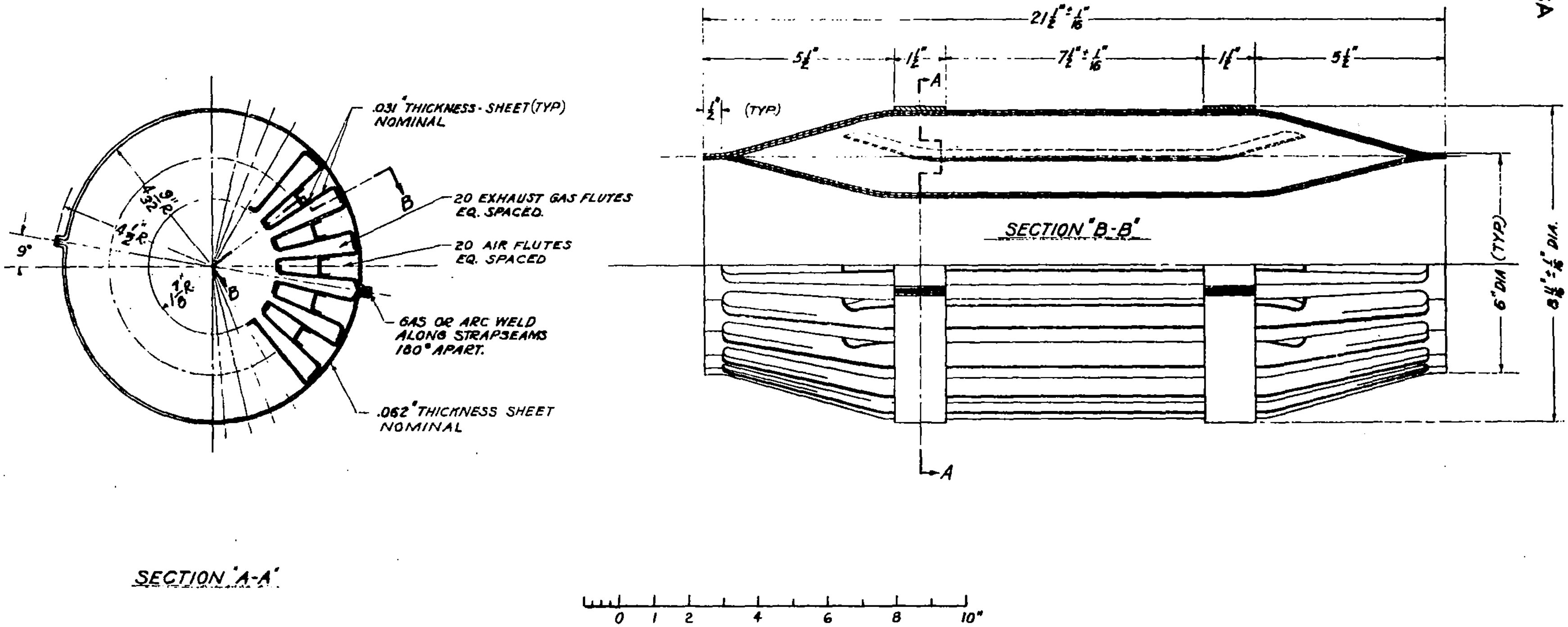


FIGURE 6.-DIAGRAM OF AIR-SIDE SHROUDING USED IN FLIGHT TESTS OF HEAT EXCHANGER 12



	AIR SIDE	GAS SIDE
HEAT TRANSFER AREA	12.5 SQ FT	11.0 SQ FT
MINIMUM FREE AREA	0.15 SQ FT	0.22 SQ FT
WETTED PERIMETER	12.0 FT.	9.60 FT.
HEAT TRANSFER PERIMETER	9.4 FT.	8.50 FT.

FABRICATION - SEAM WELDED
MATERIAL - 18-8 STAINLESS STEEL
WEIGHT OF UNIT - 22.5 LBS

FIGURE 7-HEAT EXCHANGER 29. DESIGNED AND CONSTRUCTED BY AIRESEARCH MFG. CO.

Fig. 7

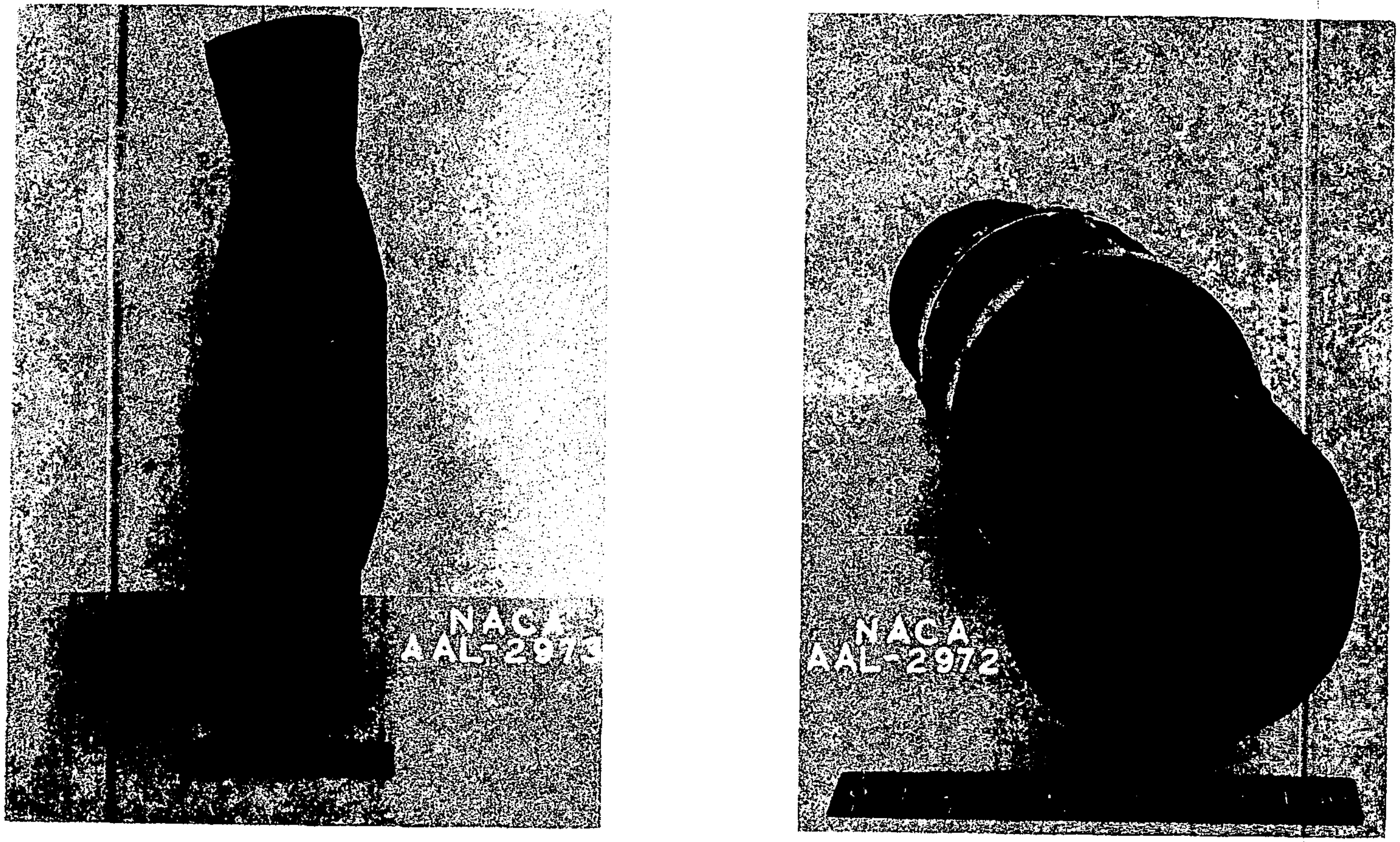


Figure 8.- Heat exchanger 29.

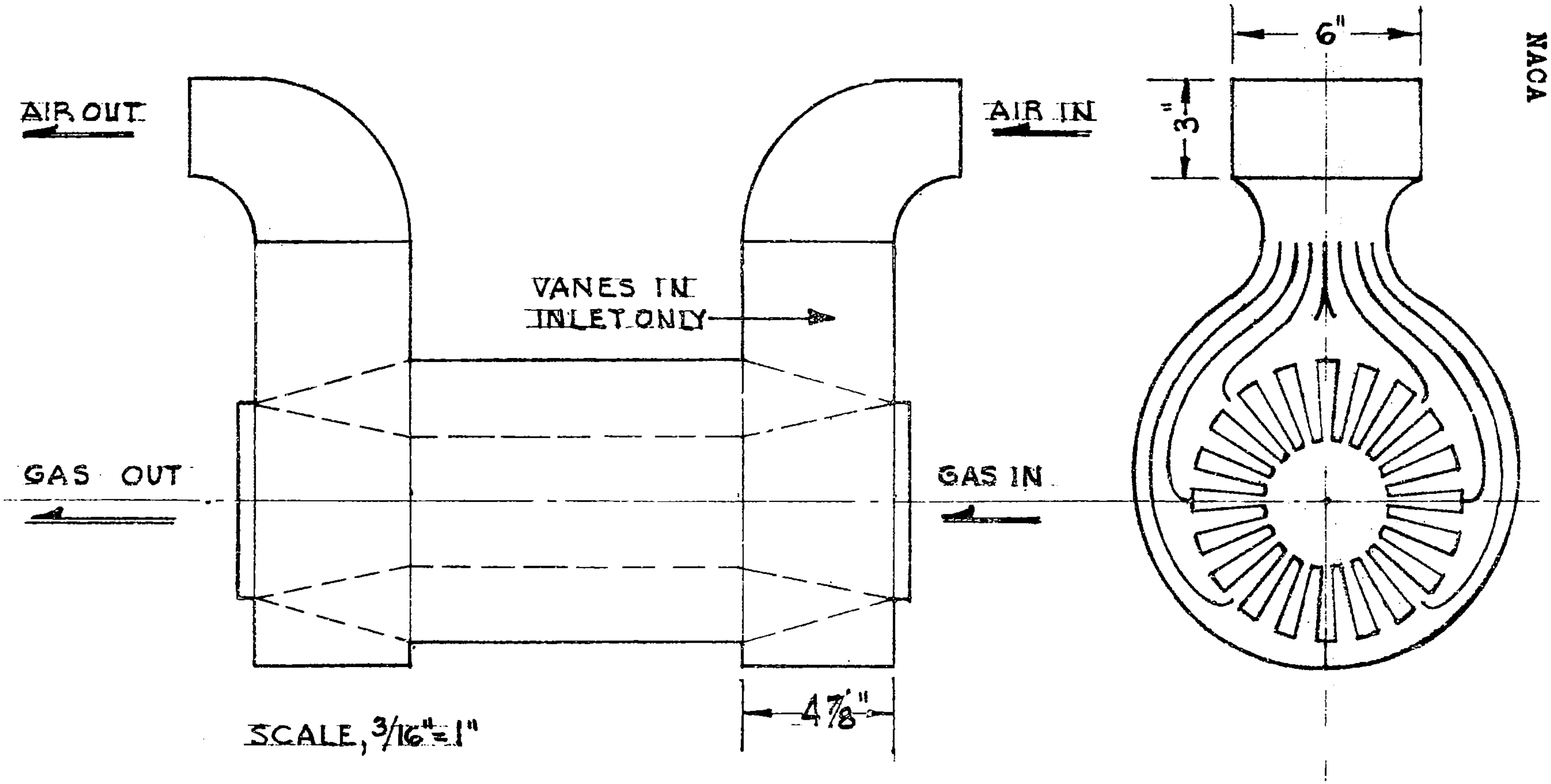
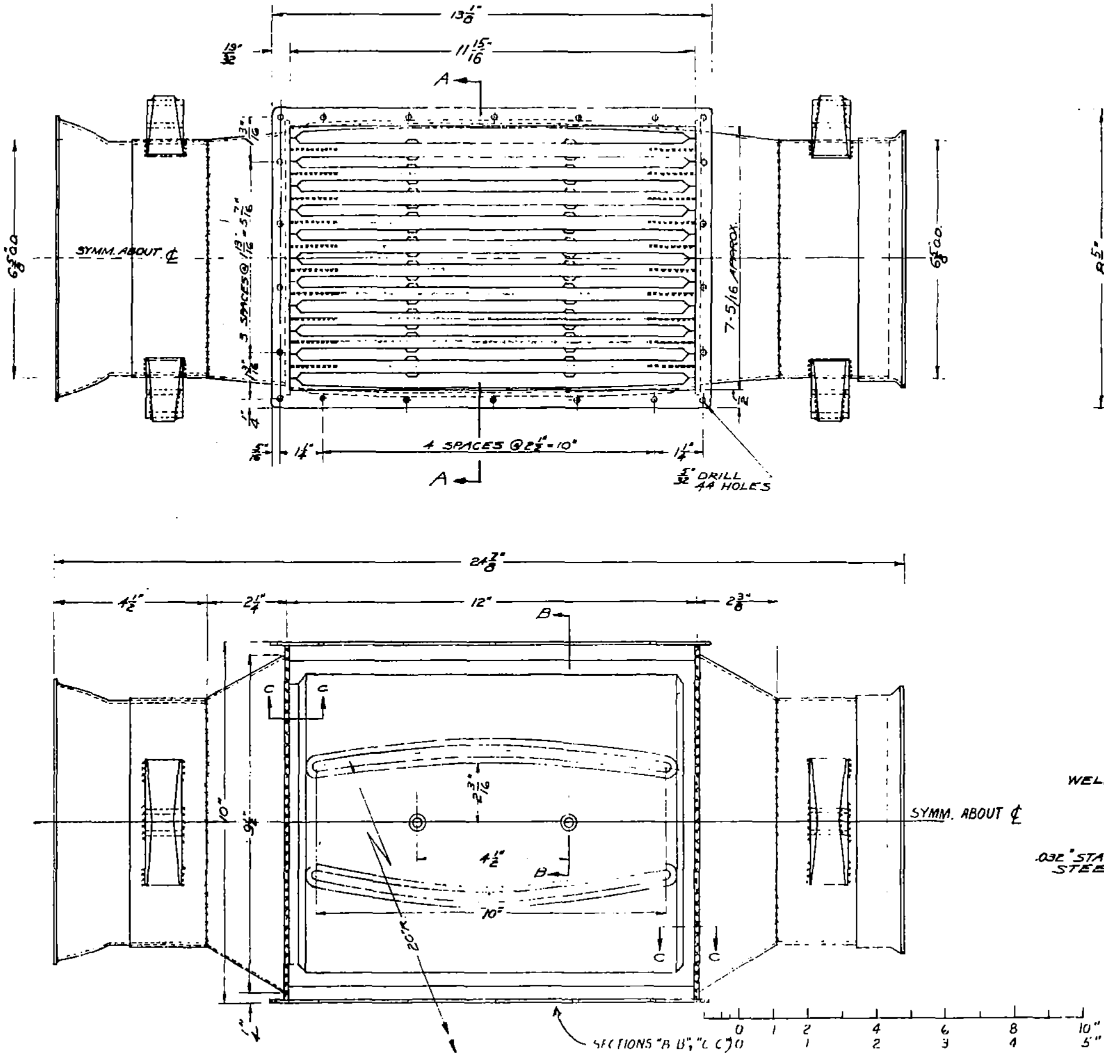
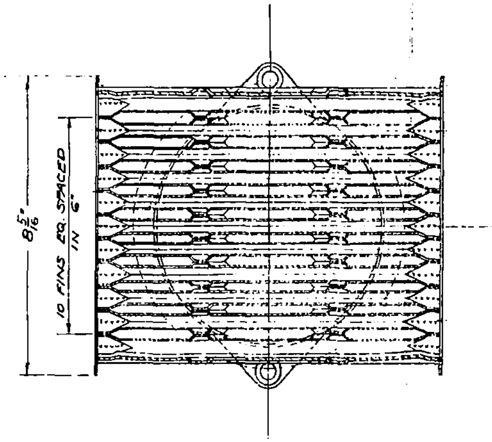
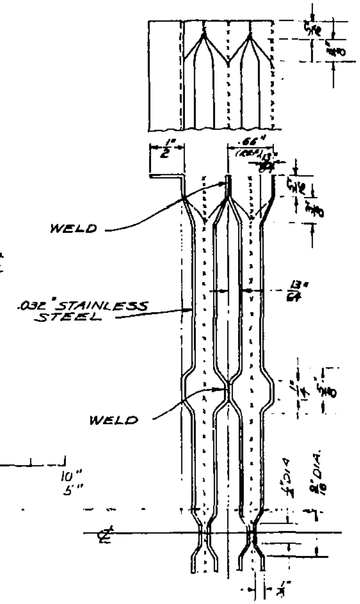


FIGURE 9. - DIAGRAM OF AIR-SIDE SHROUDING USED IN FLIGHT TESTS OF HEAT EXCHANGER 29

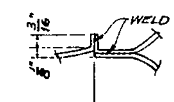




SECTION "A-A"



SECTION "B-B"
SHOWING TYPICAL
FIN CONSTRUCTION



SECTION "C-C"
(SCALE 12"=12")

FIGURE 10.- HEAT EXCHANGER 35. DESIGNED BY MATERIEL COMMAND, U.S. ARMY AIR FORCES, CONSTRUCTED BY BRIGGS MFG. CO.

HEATER ASSEMBLY STAINLESS STEEL

	AIR SIDE	GAS SIDE
HEAT TRANSFER AREA	13.80 SQ FT	13.80 SQ FT
MINIMUM FREE AREA	0.21 SQ FT	0.20 SQ FT
WETTED PERIMETER	20.6 FT	15.0 FT
HEAT TRANSFER PERIMETER	18.7 FT	11.0 FT

FABRICATION - SEAM AND SPOTWELDED
MATERIALS 18-8 STAINLESS STEEL
WEIGHT OF UNIT [illegible]½ LBS

Figure 11.- Heat exchanger 35.

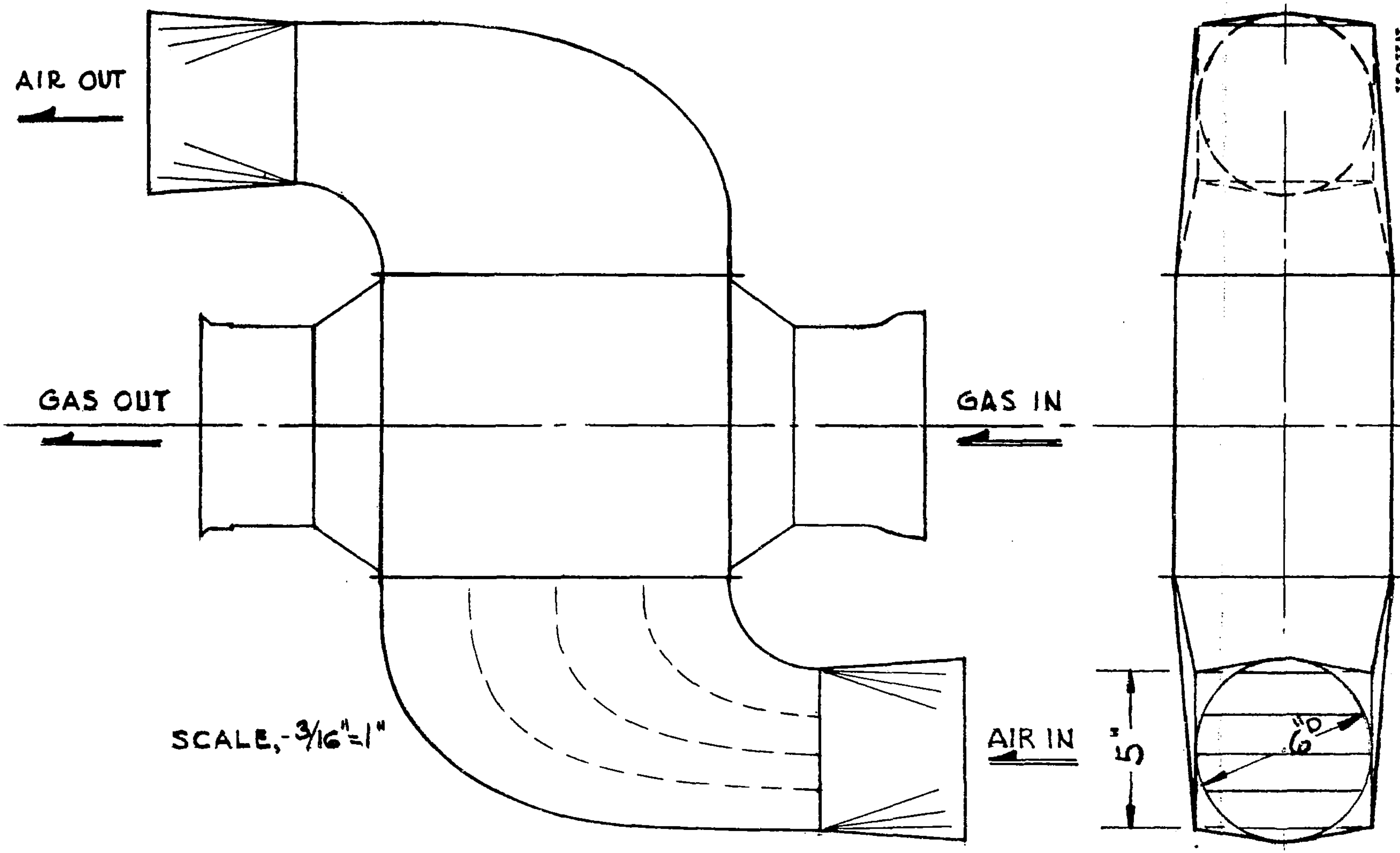


FIGURE 12.-DIAGRAM OF AIR-SIDE SHROUDING USED IN FLIGHT TESTS OF HEAT EXCHANGER 35

NACA

Fig. 12

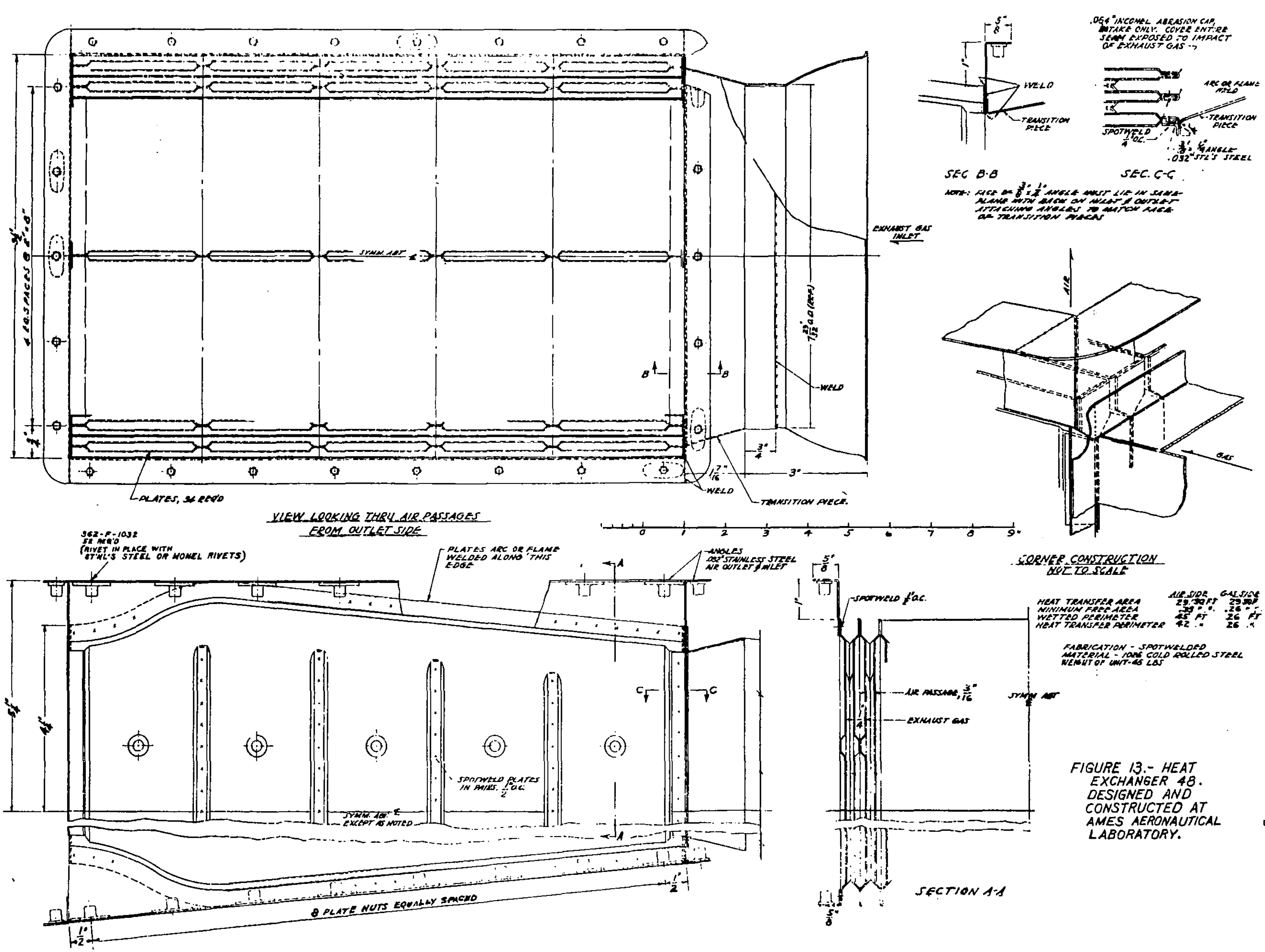


FIGURE 13.- HEAT EXCHANGER 48. DESIGNED AND CONSTRUCTED AT AMES AERONAUTICAL LABORATORY.

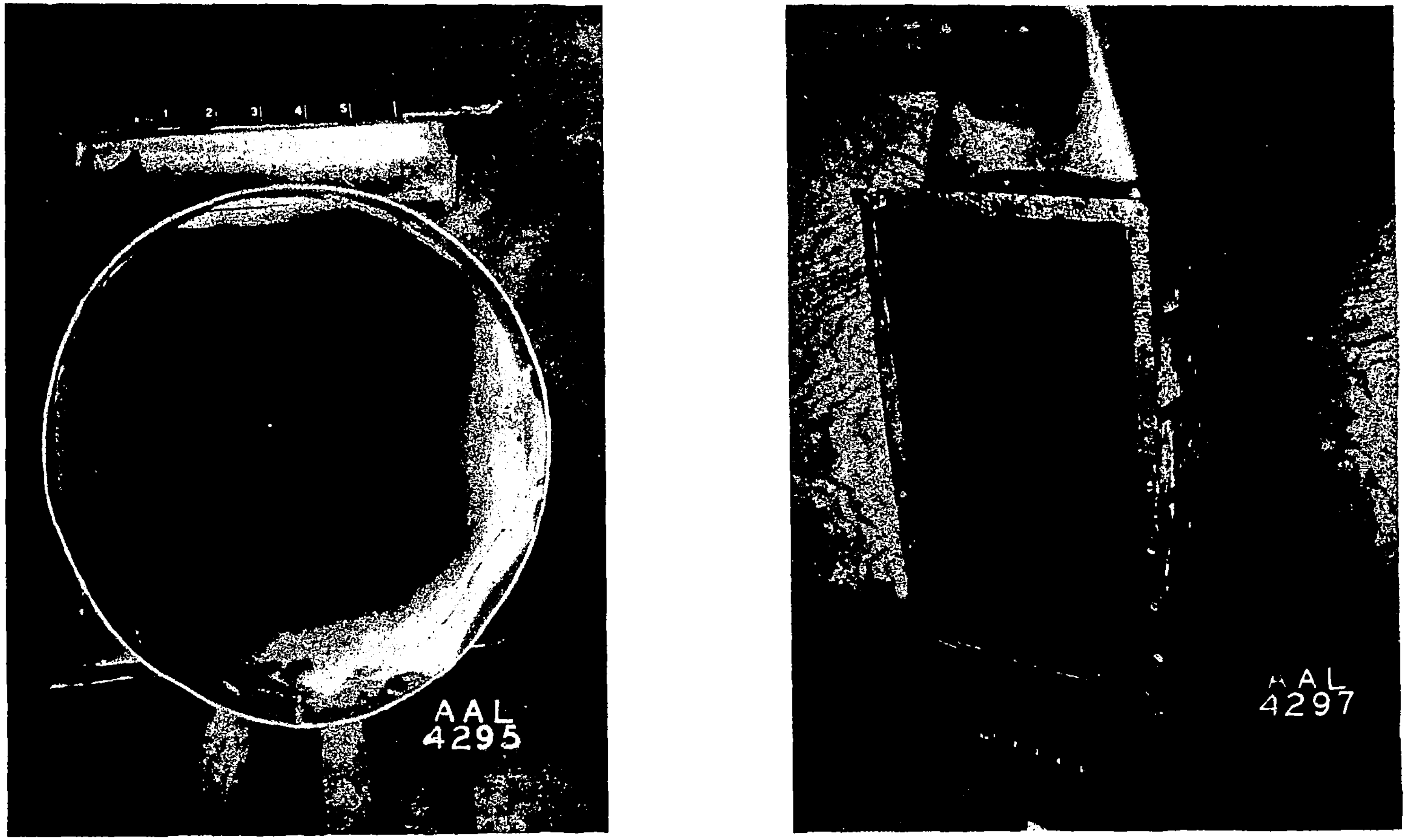


Figure 14.- Heat exchanger 48

NACA

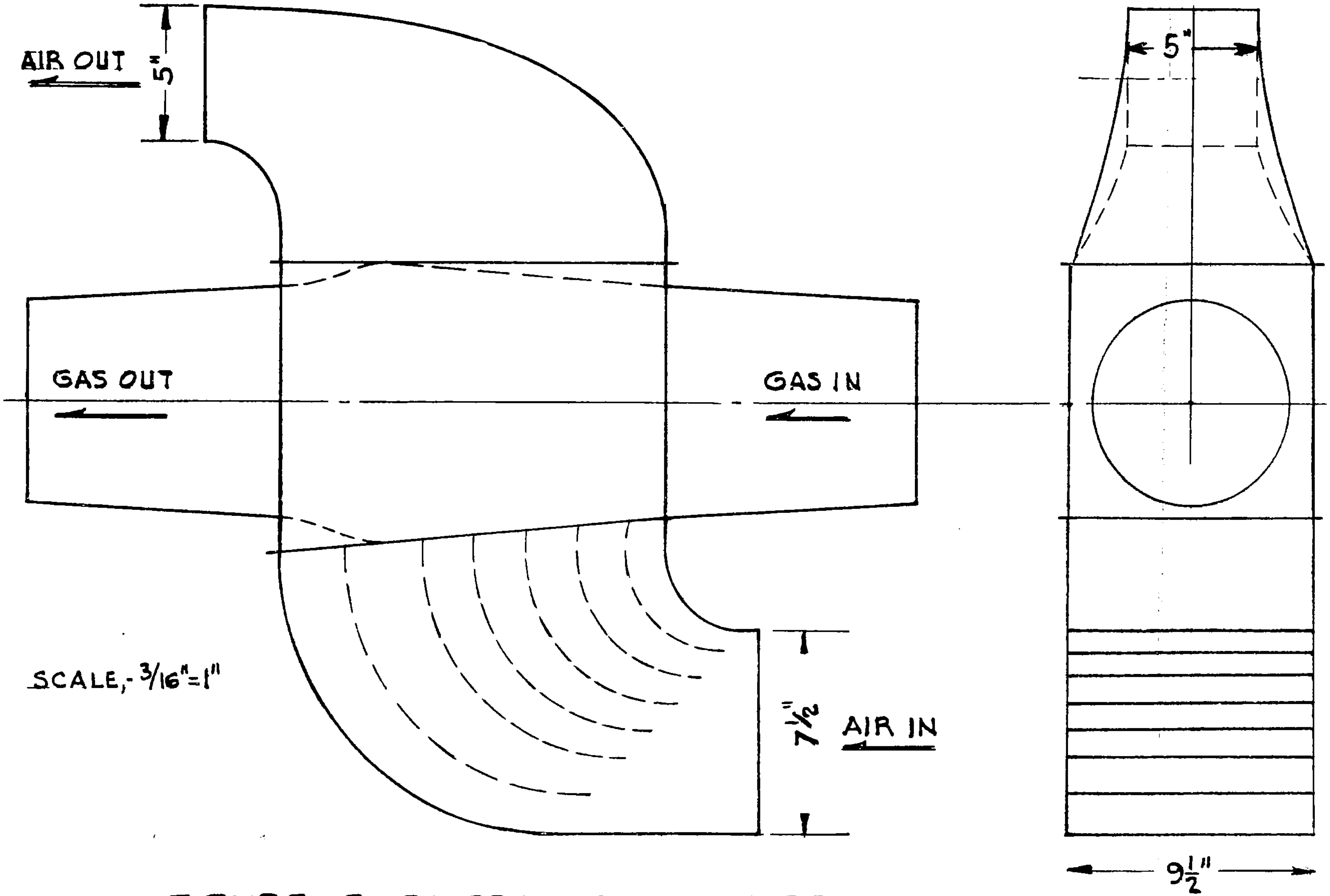
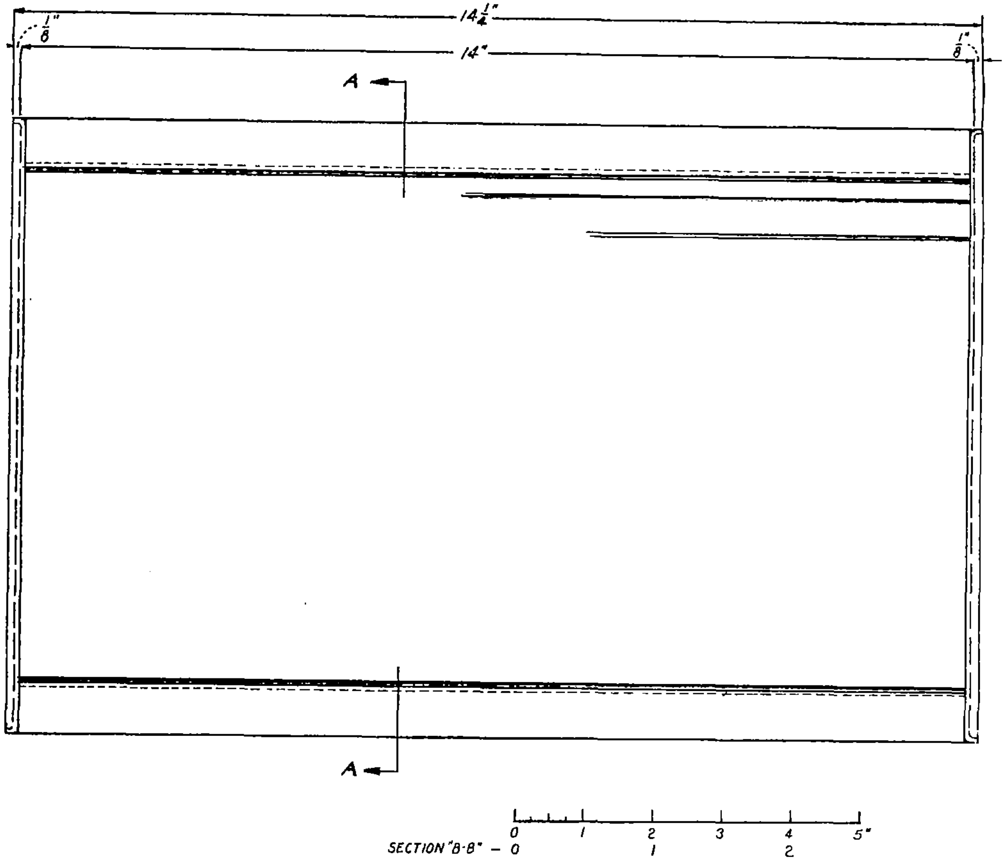
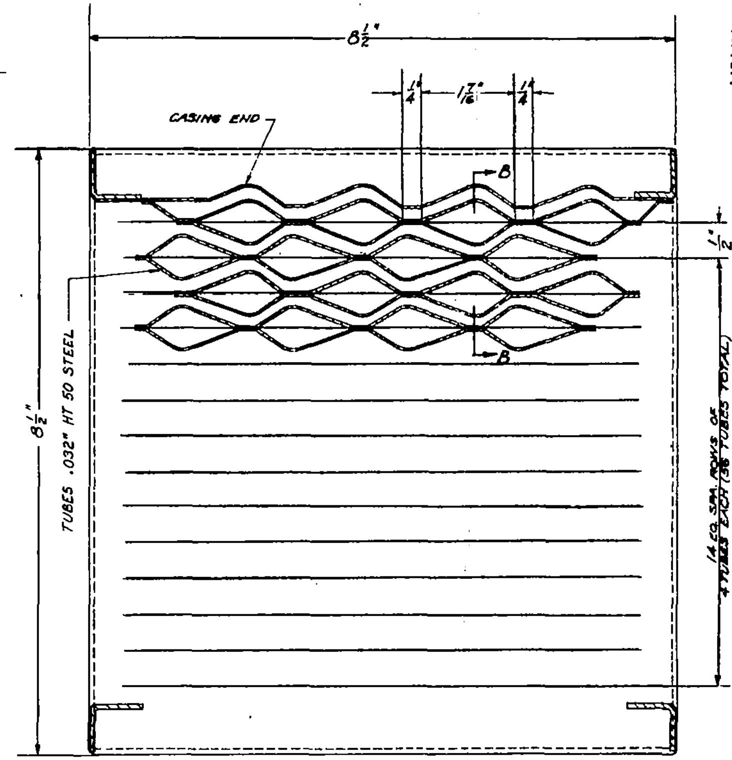


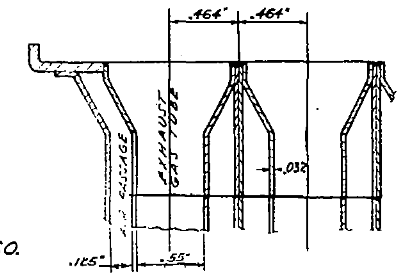
Fig. 15

FIGURE 15.-DIAGRAM OF AIR-SIDE SHROUDING USED IN FLIGHT TESTS OF HEAT EXCHANGER 48





SECTION "A-A"



SECTION "B B"

	AIR SIDE	GAS SIDE
HEAT TRANSFER AREA	19.0 SQ FT	16.5 SQ FT
MINIMUM FREE AREA	0.18 SQ FT	0.15 SQ FT
WETTED PERIMETER	34.70 FT	14.60 FT
HEAT TRANSFER PERIMETER	30.00 FT	14.60 FT

FABRICATION - TORCH WELDED
MATERIAL - HT 50 STEEL
WEIGHT OF UNIT - $32\frac{1}{4}$ LBS

FIGURE 16. -
HEAT EXCHANGER II. DESIGNED AND CONSTRUCTED BY TRANE MFG. CO.

Fig. 16

Figure 17.- Heat exchanger 11.

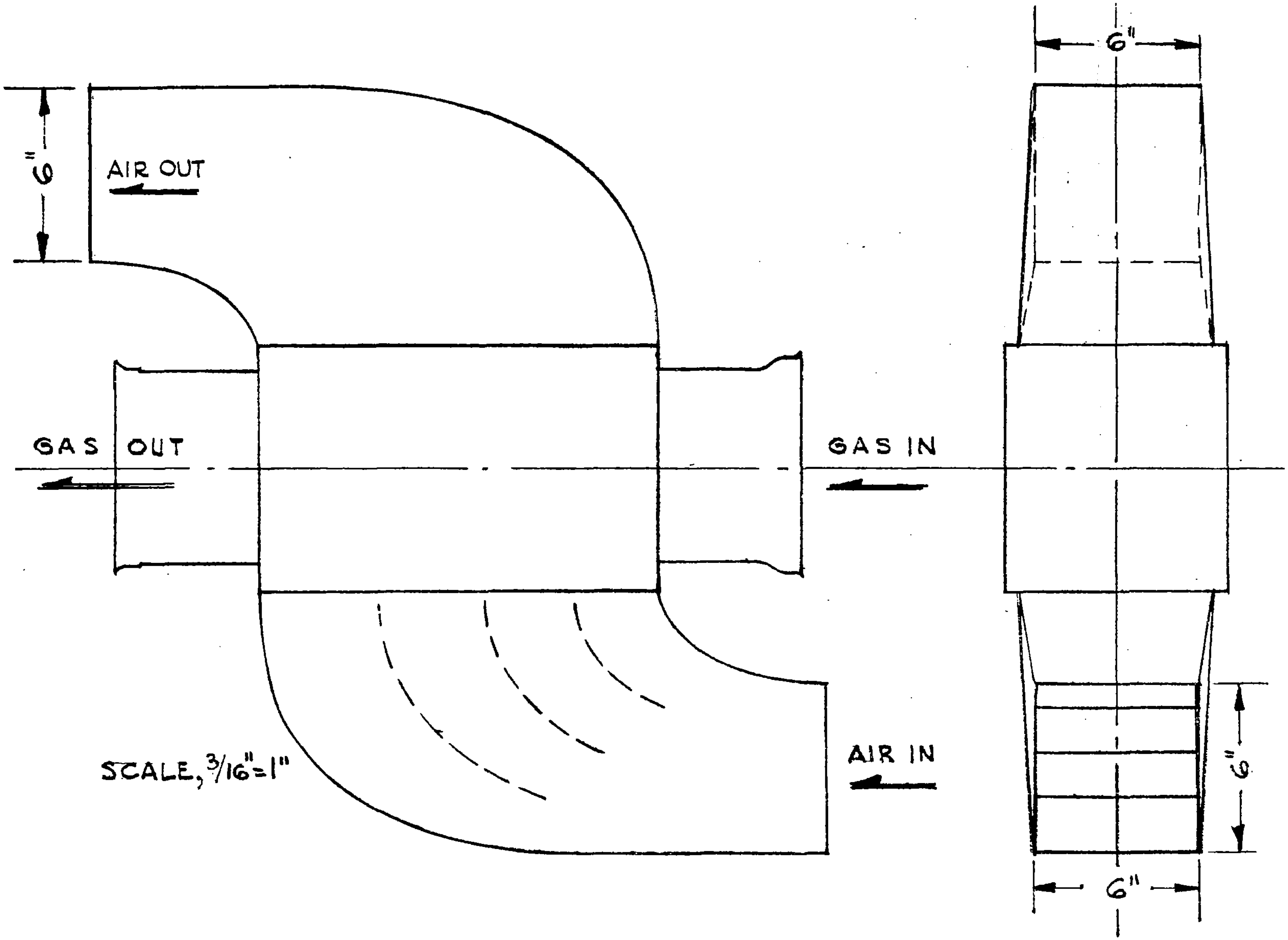
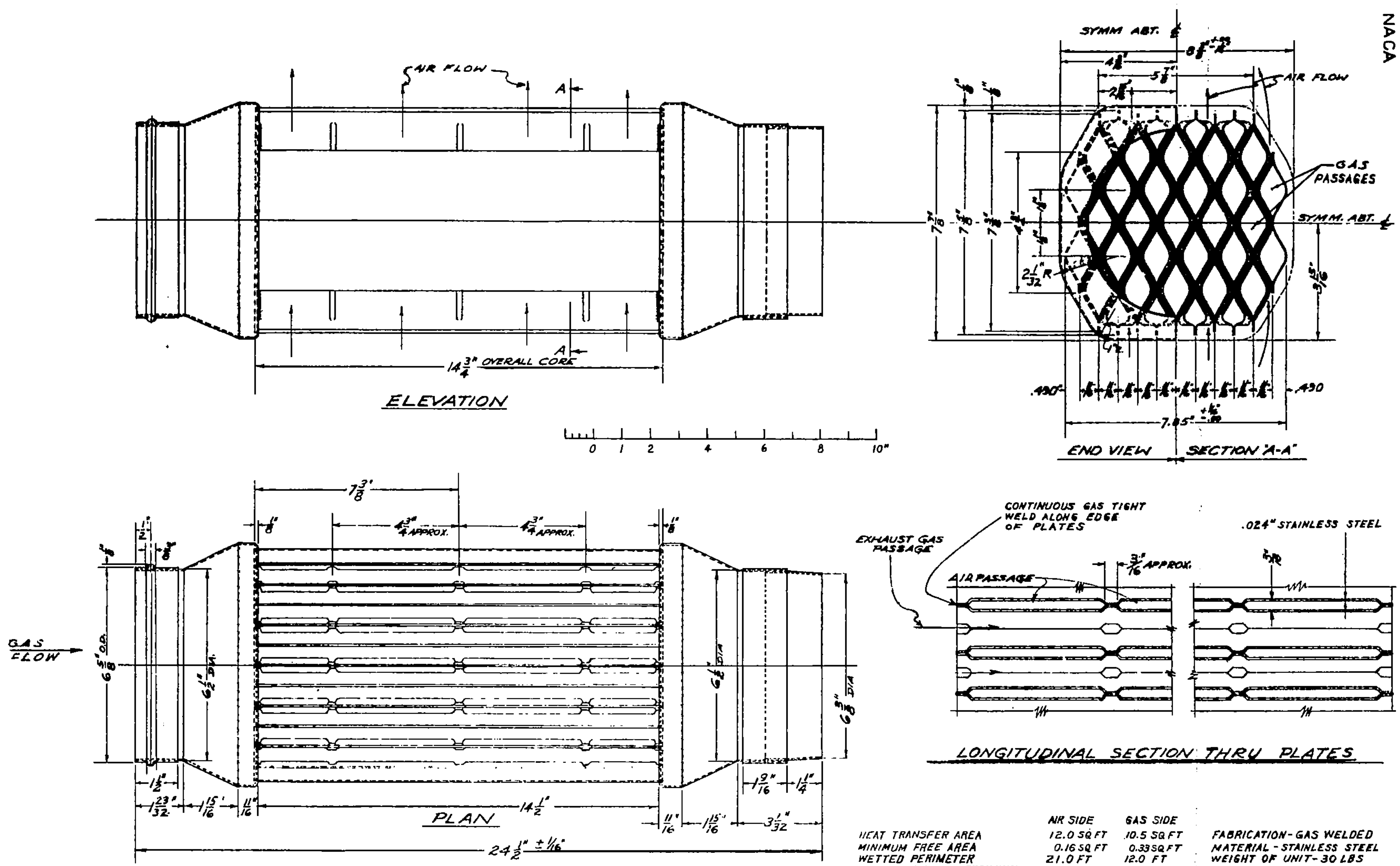


FIGURE 18.-DIAGRAM OF AIR-SIDE SHROUDING USED IN FLIGHT TESTS OF HEAT EXCHANGER 11



	AIR SIDE	GAS SIDE
HEAT TRANSFER AREA	12.0 SQ FT	10.5 SQ FT
MINIMUM FREE AREA	0.16 SQ FT	0.33 SQ FT
WETTED PERIMETER	21.0 FT	12.0 FT
HEAT TRANSFER PERIMETER	19.0 FT	12.0 FT

FABRICATION - GAS WELDED
MATERIAL - STAINLESS STEEL
WEIGHT OF UNIT - 30 LBS

FIGURE 19.- HEAT EXCHANGER 42. DESIGNED AND CONSTRUCTED BY TRANE MFG.CO.

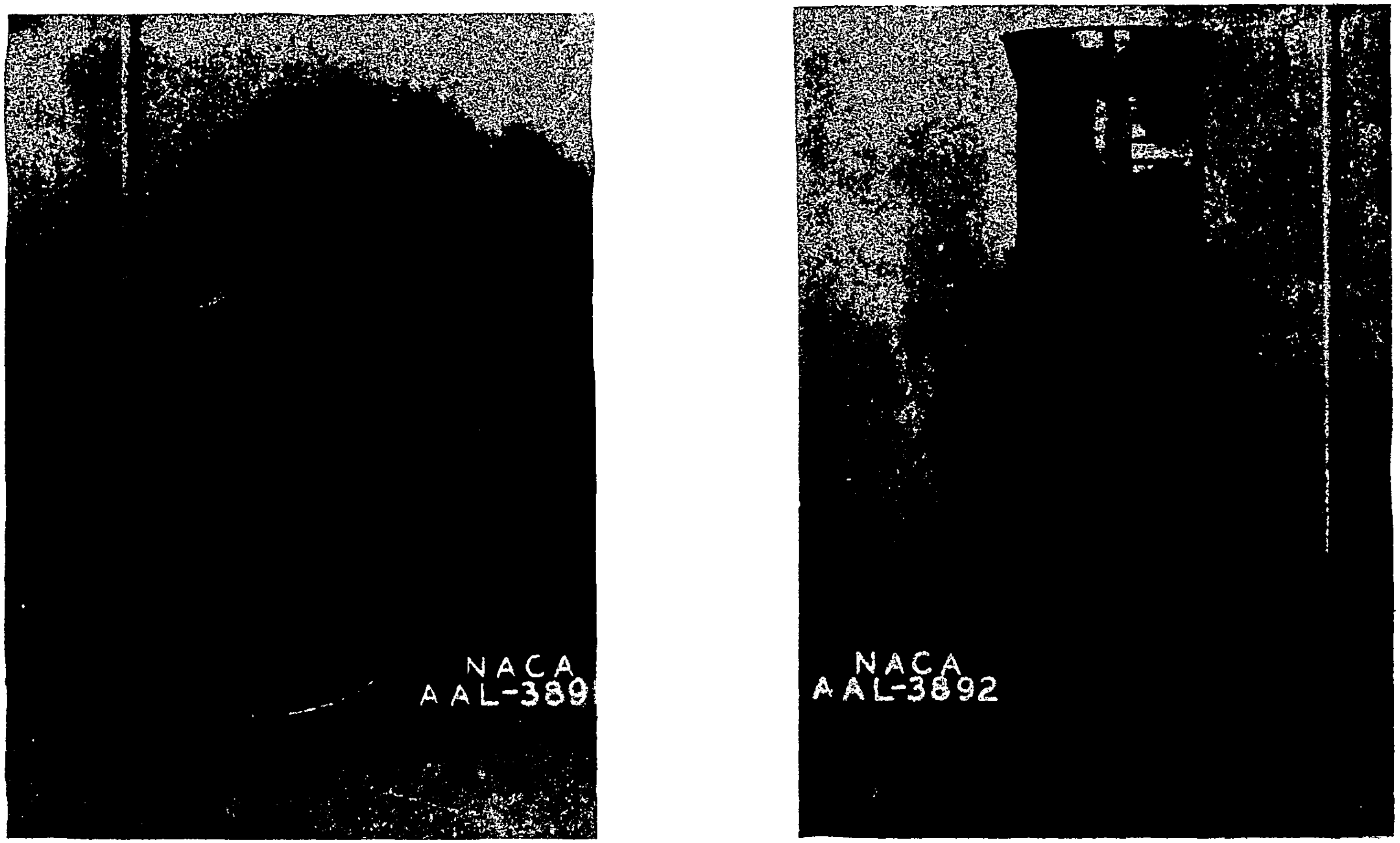


Figure 20.- Heat exchanger 42.

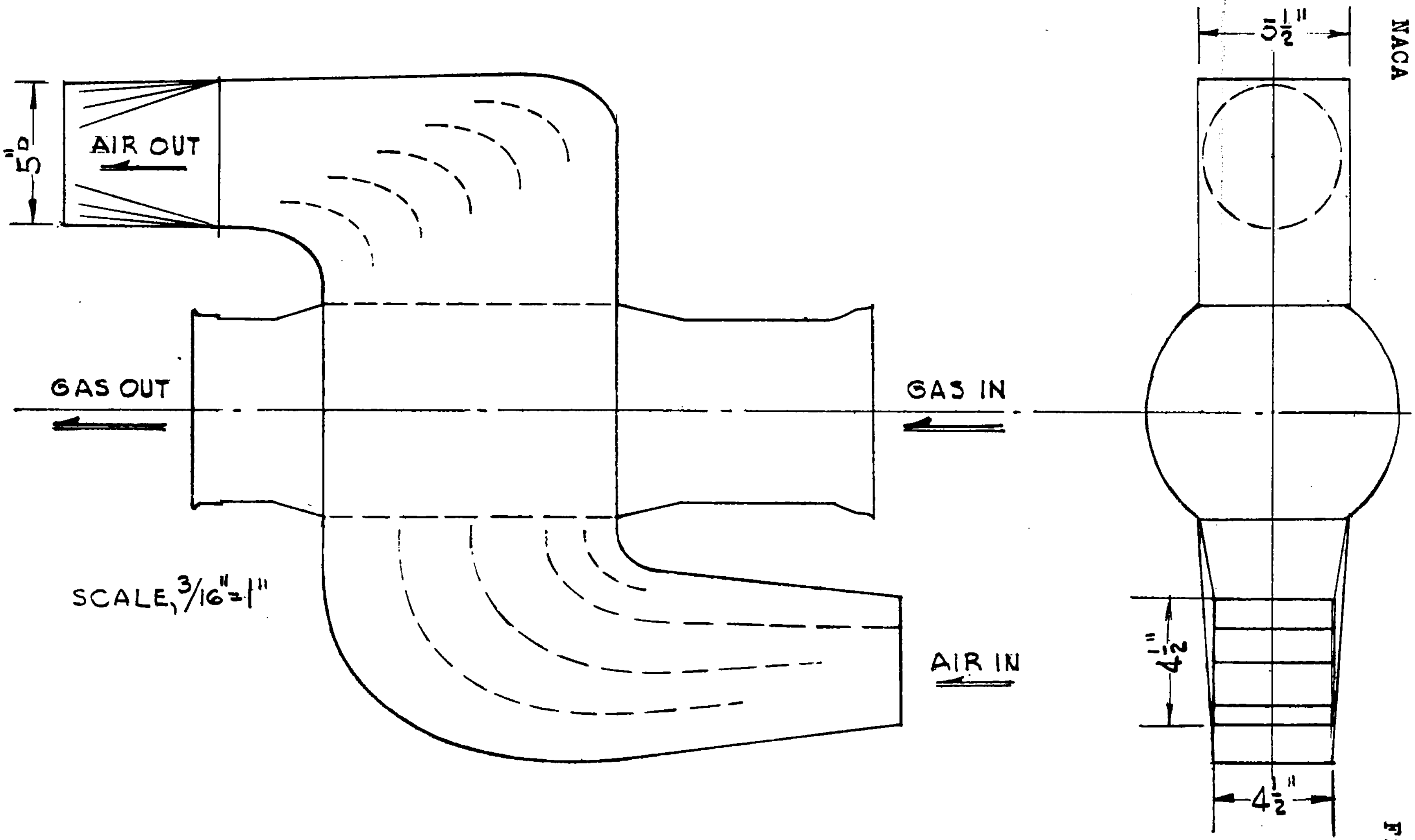


FIGURE 21.-DIAGRAM OF AIR-SIDE SHROUDING USED IN FLIGHT TESTS OF HEAT EXCHANGER 42

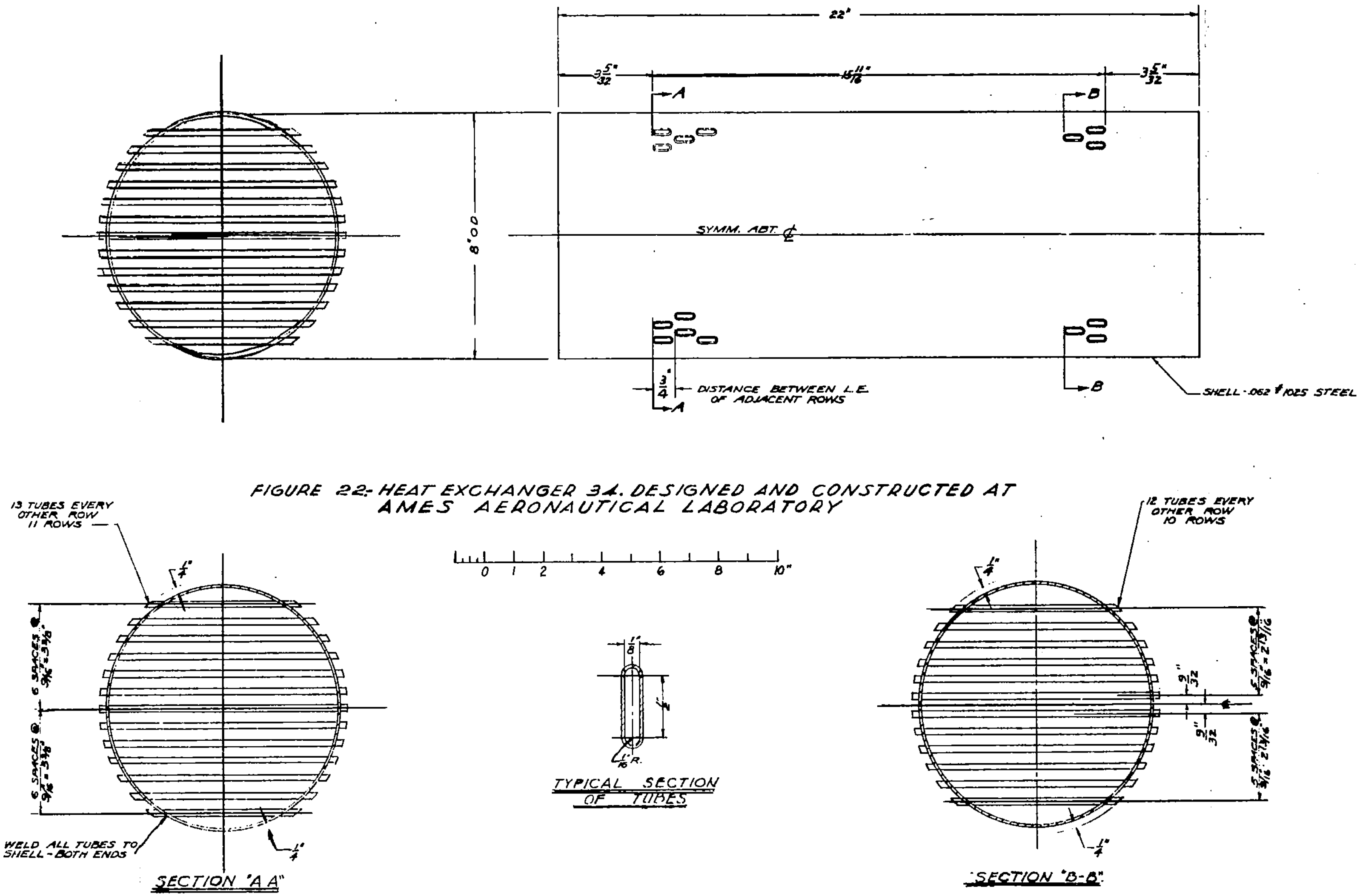
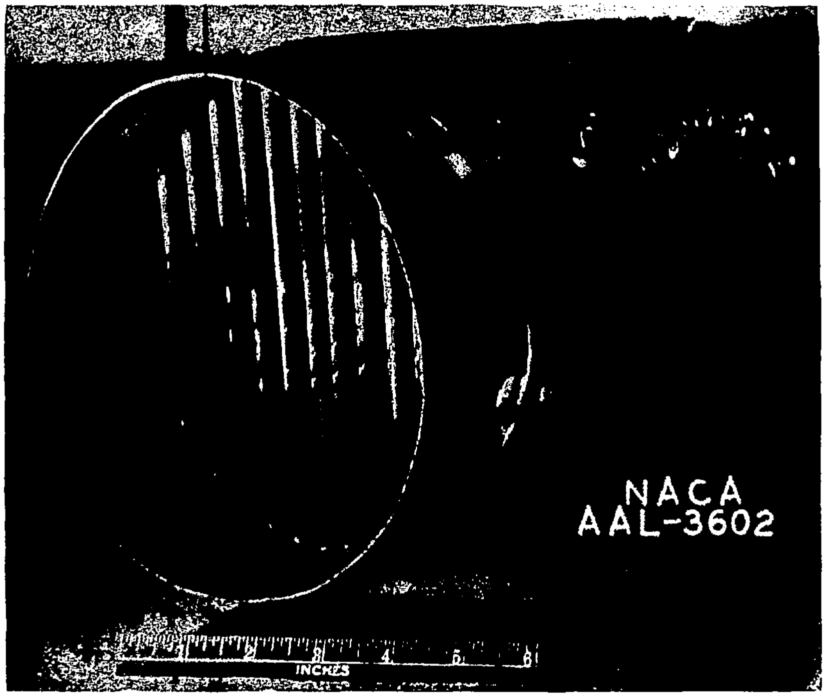


FIGURE 22- HEAT EXCHANGER 34. DESIGNED AND CONSTRUCTED AT AMES AERONAUTICAL LABORATORY

	AIR SIDE	GAS SIDE
HEAT TRANSFER AREA	[illegible] SQ FT	[illegible] SQ FT
MINIMUM FREE AREA	[illegible] SQ FT	[illegible]
WETTED PERIMETER	[illegible] FT	[illegible]
HEAT TRANSFER PERIMETER	[illegible] FT	[illegible]

FABRICATION - TUBES TORCH WELDED TO SHELL
MATERIALS - 1025 STEEL
WEIGHT OF UNIT - 30 LBS



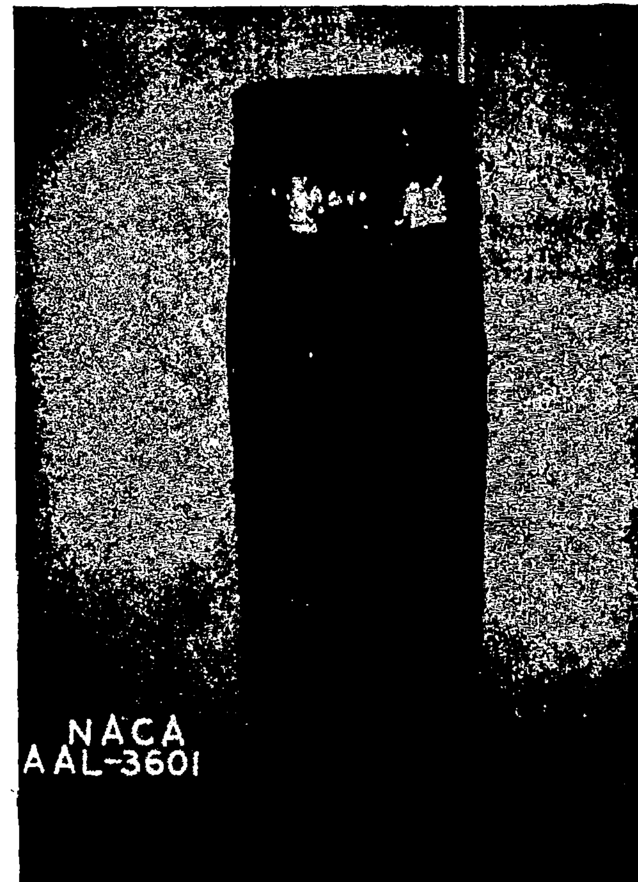


Figure 23.- Heat exchanger 34

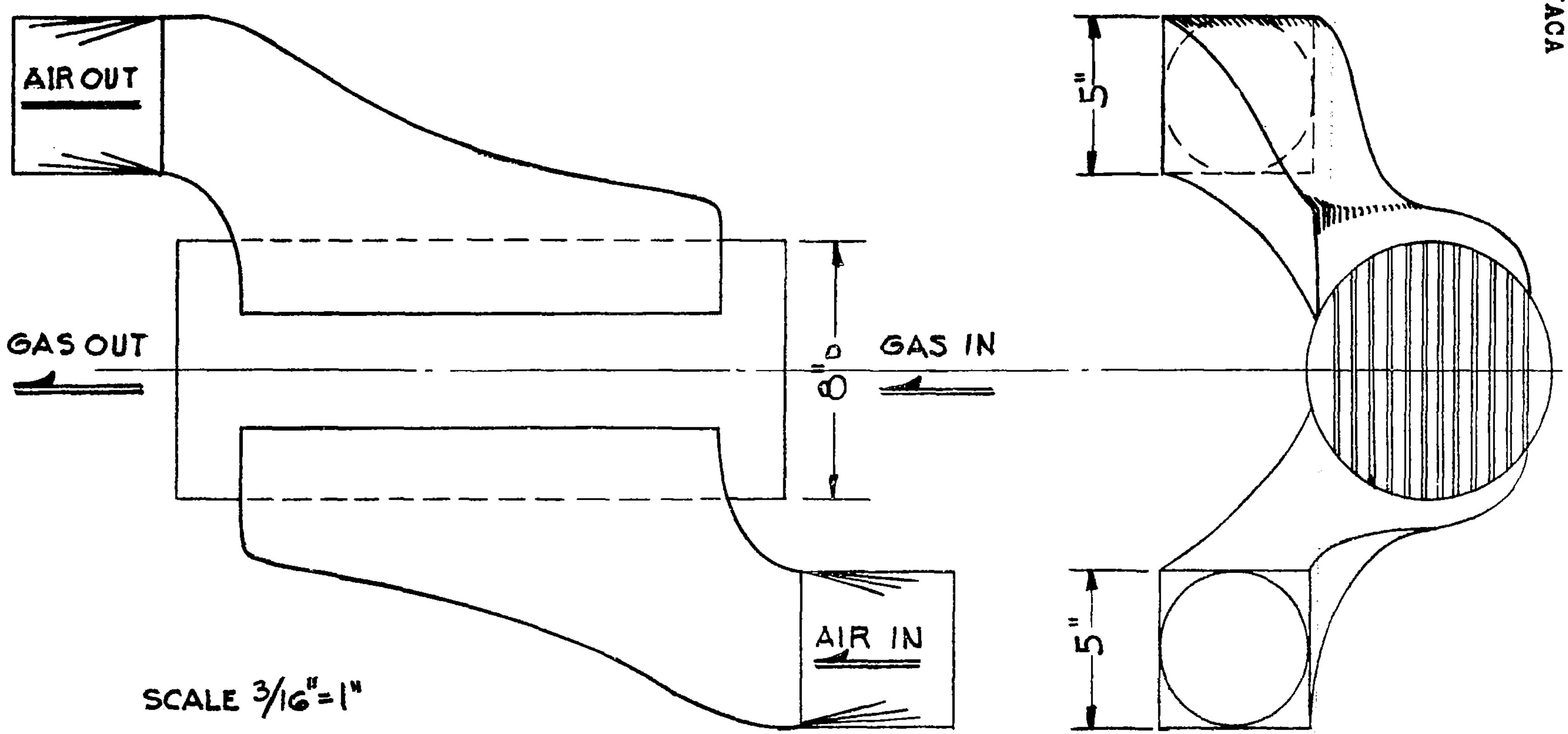
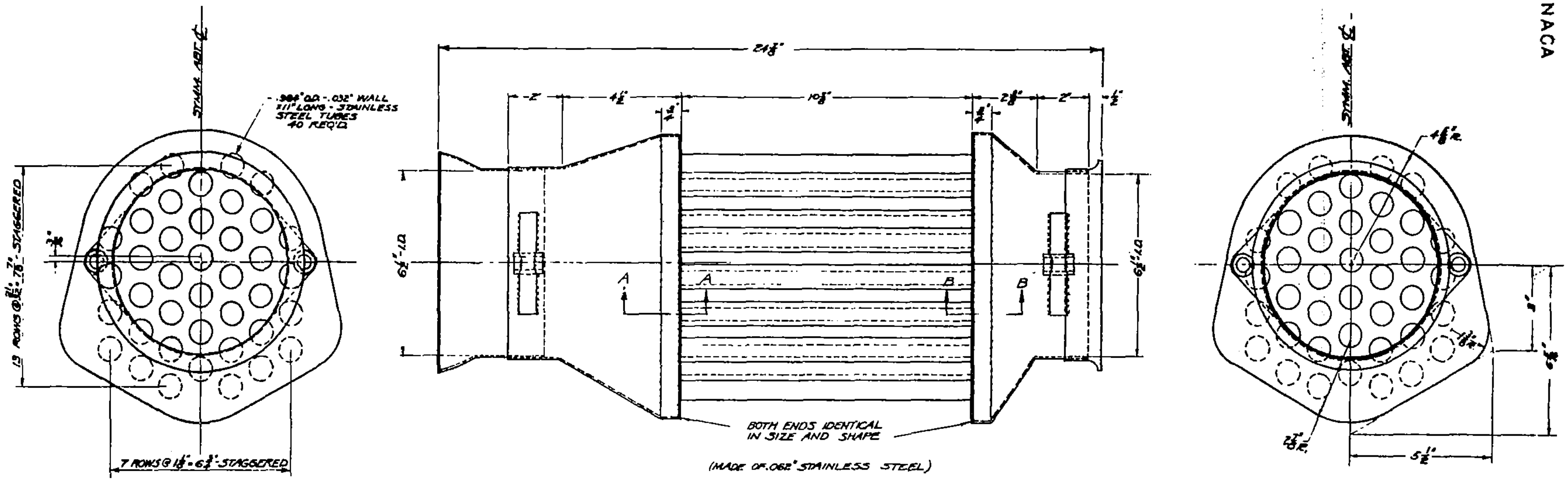
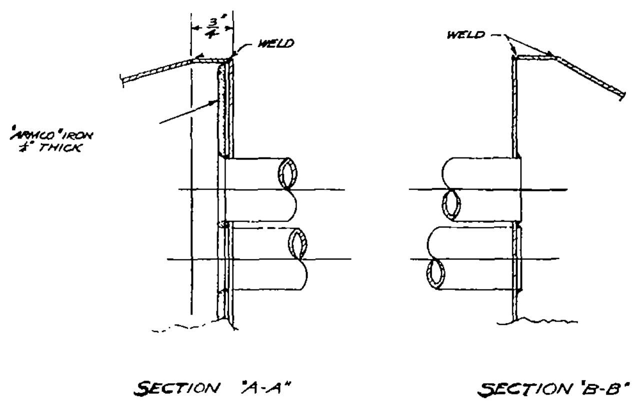
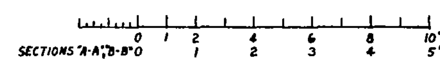


FIGURE 24.- DIAGRAM OF AIR-SIDE SHROUDING USED IN FLIGHT TESTS OF HEAT EXCHANGER 34







	AIR SIDE	GAS SIDE
HEAT TRANSFER AREA	9.30 SQ FT	8.15 SQ FT
MINIMUM FREE AREA	——	0.16 SQ FT
WETTED PERIMETER	——	9.0 FT
HEAT TRANSFER PERIMETER	——	9.0 FT

FABRICATION - TUBES TORCH WELDED TO FLANGES
MATERIAL - 18-8 STAINLESS STEEL
WEIGHT OF UNIT - 29-3/4 LBS

FIGURE 25 - HEAT EXCHANGER 39. DESIGNED AND CONSTRUCTED BY STEWART WARNER CORP.

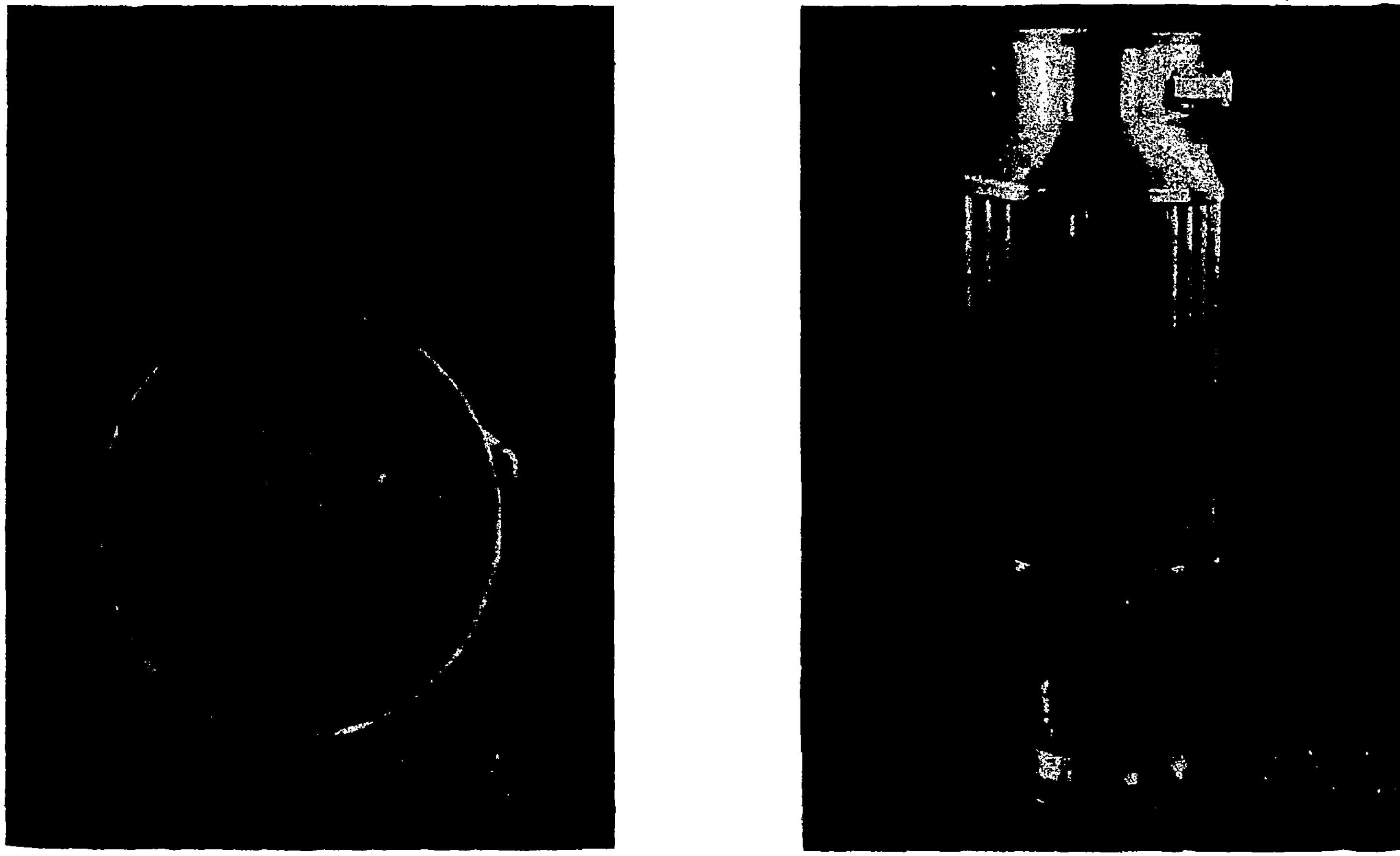


Figure 26.- Heat exchanger 39

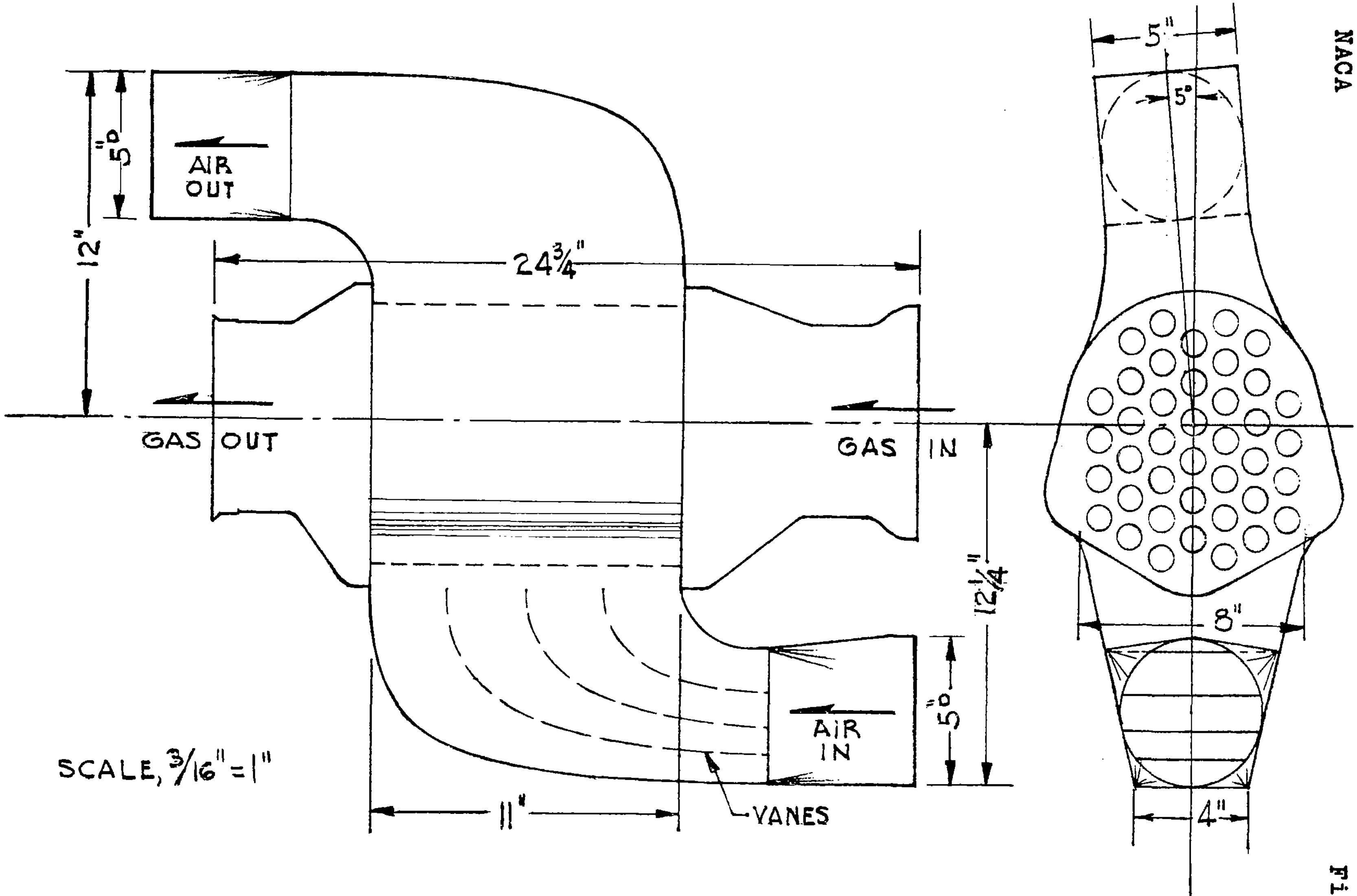
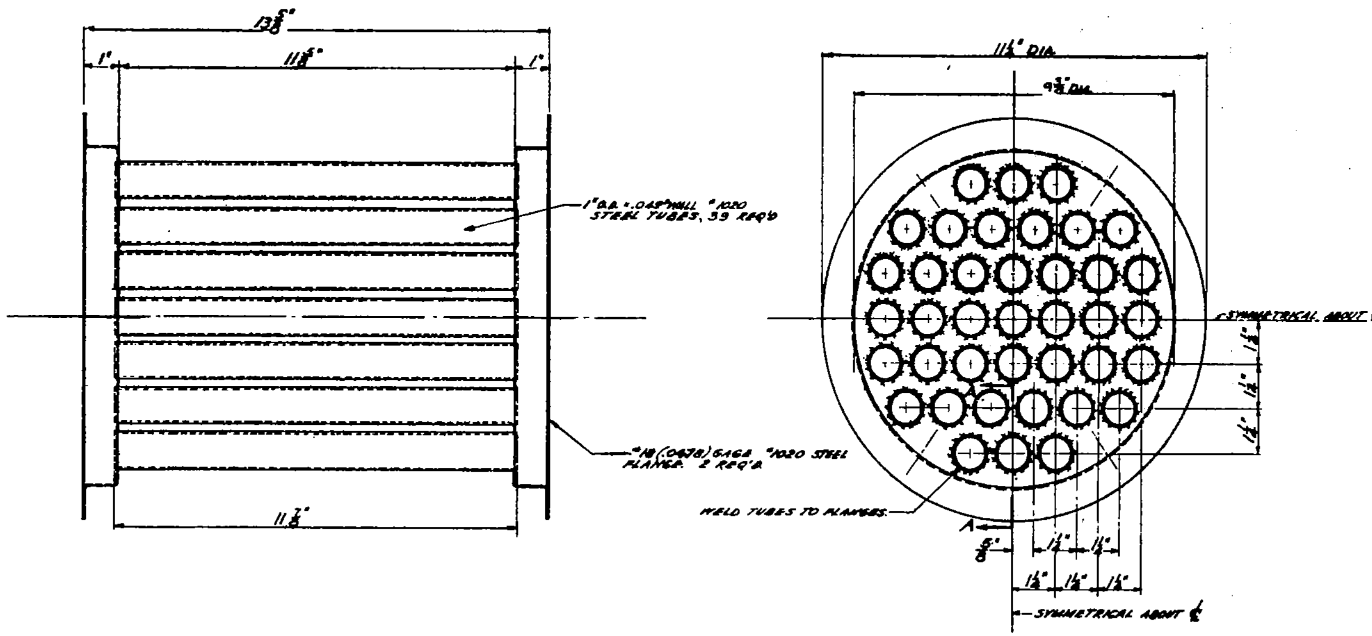
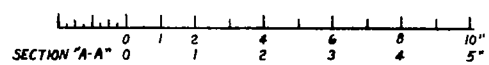
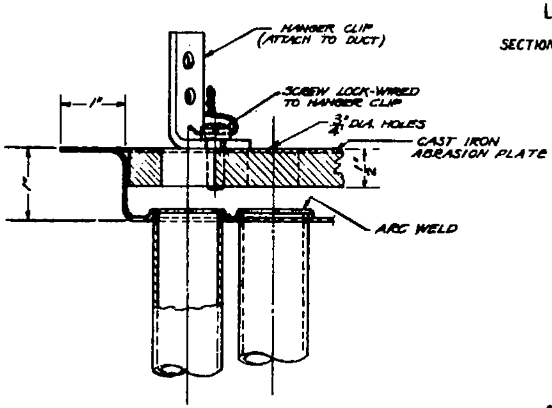


FIGURE 27.-DIAGRAM OF AIR-SIDE SHROUDING USED IN FLIGHT TESTS OF HEAT EXCHANGER 39



ASSEMBLY



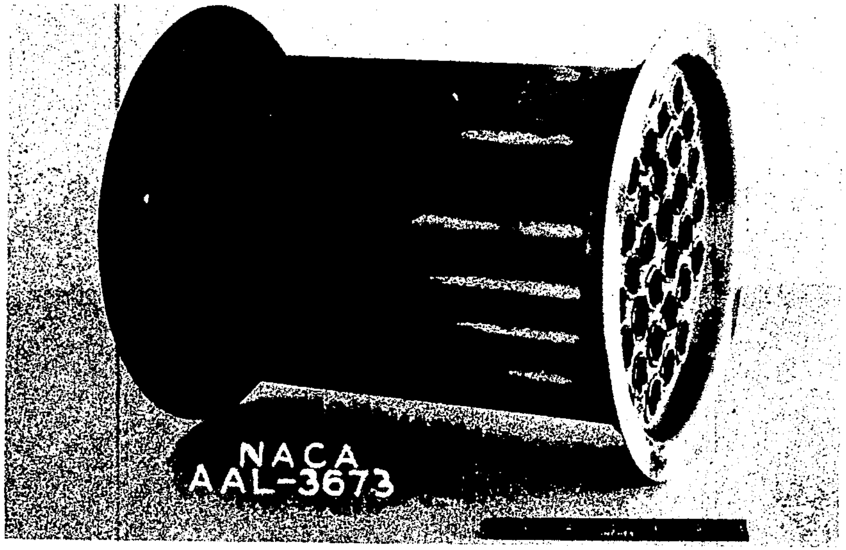


SECTION "A-A"

	AIR SIDE	GAS SIDE
HEAT TRANSFER AREA	9.90 SQ FT	8.90 SQ FT
MINIMUM FREE AREA	—	0.17 SQ FT
WETTED PERIMETER	—	9.20 FT
HEAT TRANSFER PERIMETER	—	9.20 FT

FABRICATION – TUBES TORCH WELDED TO FLANGES
MATERIAL – 1020 STAINLESS STEEL
WEIGHT OF UNIT – 22 LBS.

FIGURE 28 - HEAT EXCHANGER 40. DESIGNED AND CONSTRUCTED BY M^C QUAY INC.



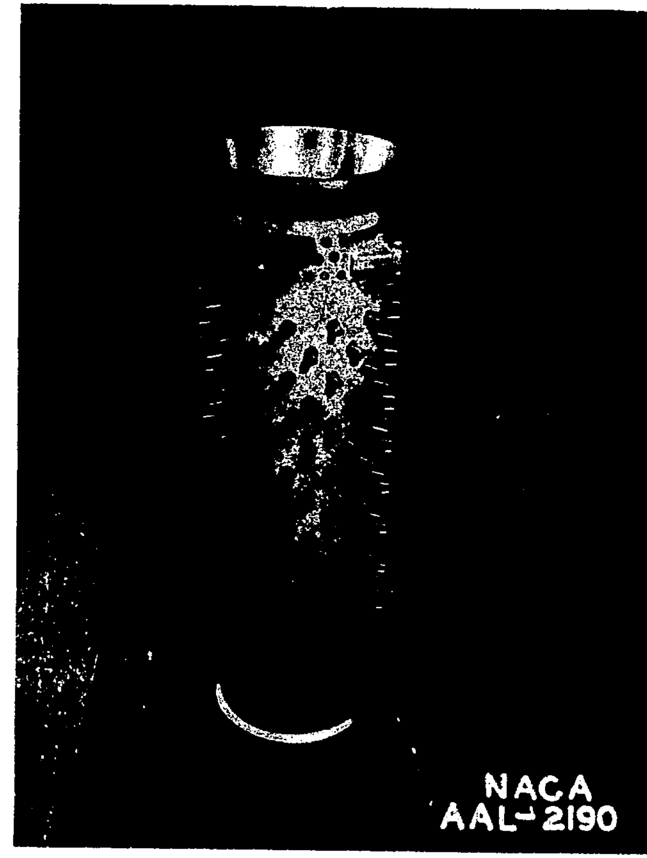


Figure 32.- Heat exchanger 4.

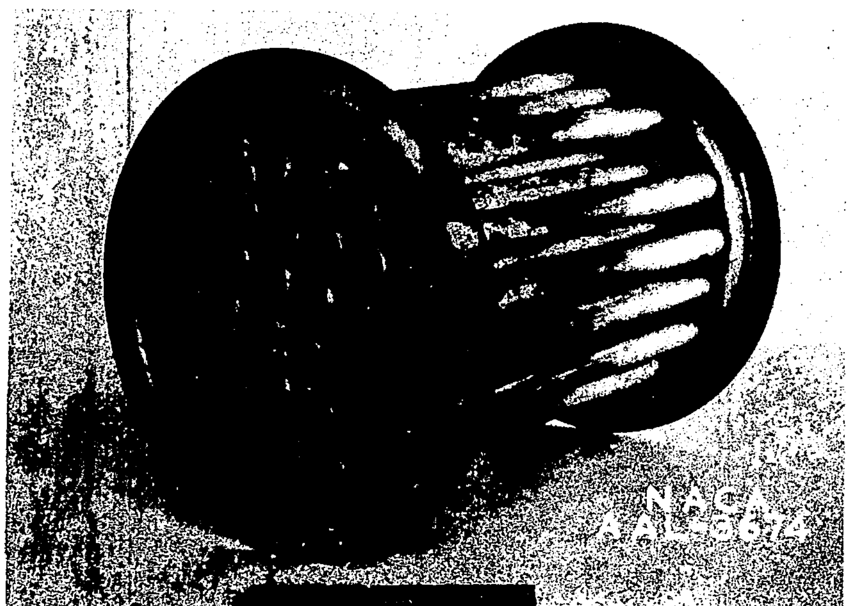


Figure 29.- Heat exchanger 40.

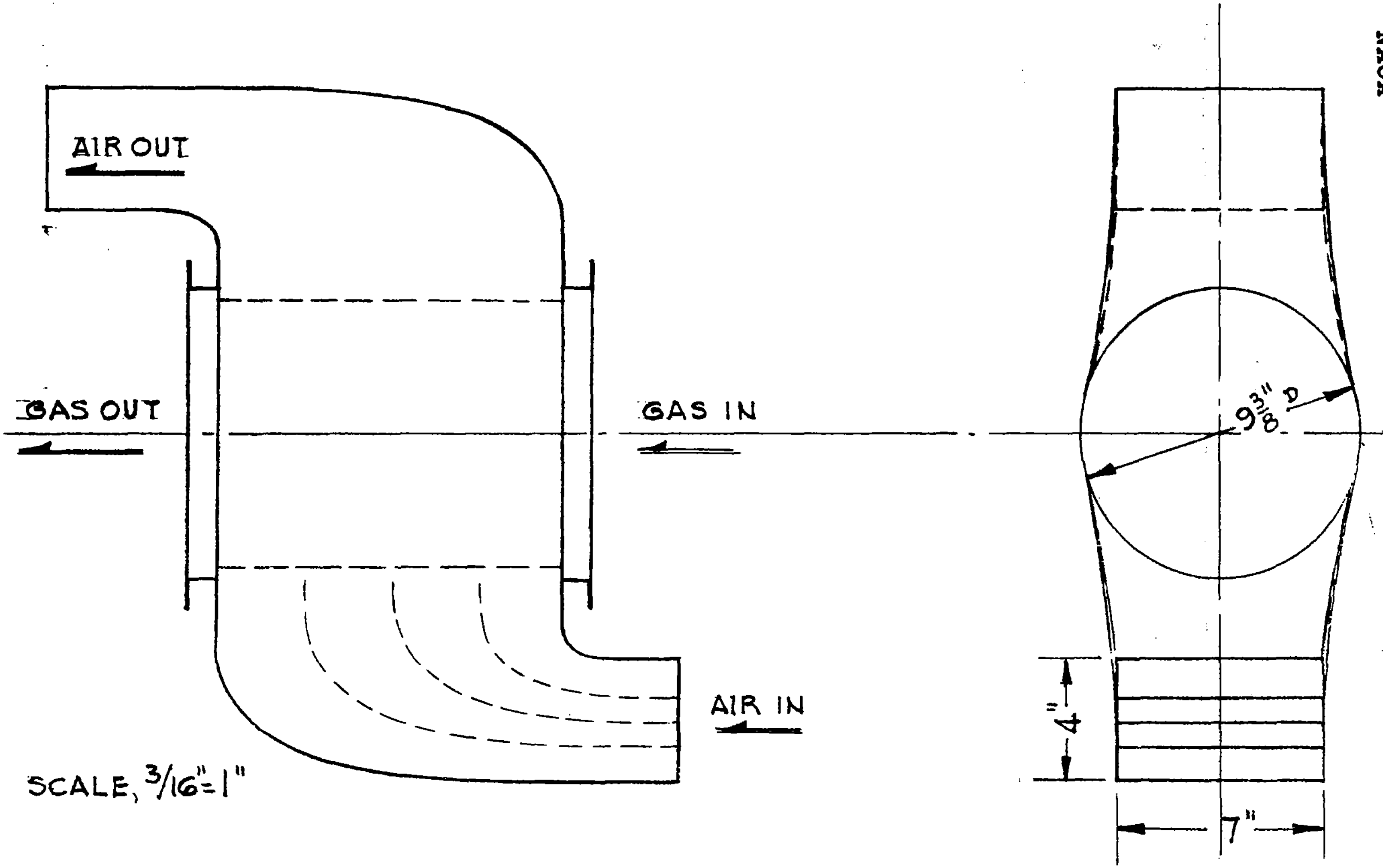
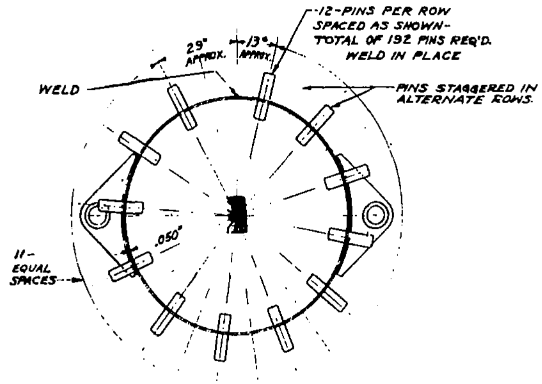
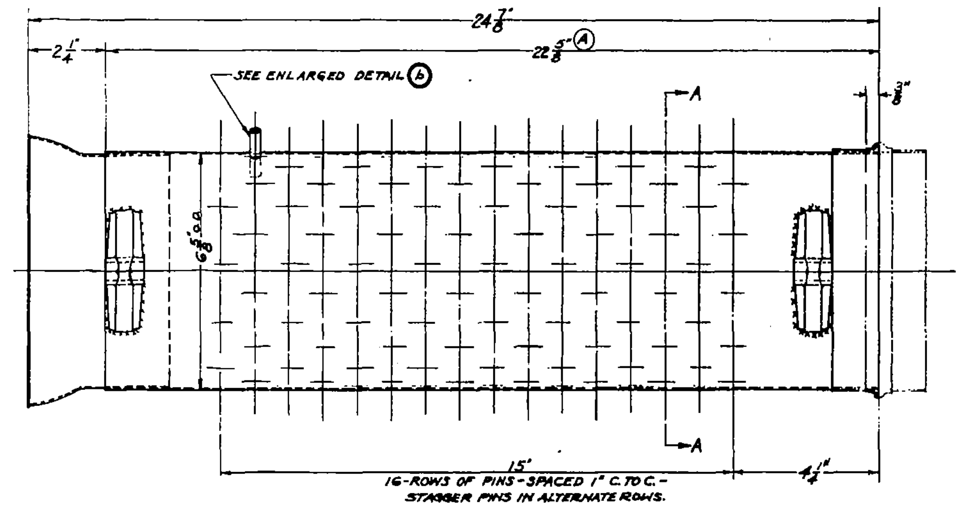


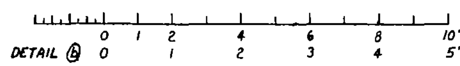
FIGURE 30.-DIAGRAM OF AIR-SIDE SHROUDING USED IN FLIGHT TESTS OF HEAT EXCHANGER 40

NACA

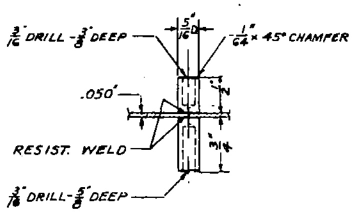


SECTION "A-A"





NOTE:
NORMALIZE, PICKLE, & PASSIVATE AFTER ASSEMBLY.



DETAIL (b)

	AIR SIDE	GAS SIDE
HEAT TRANSFER AREA	4.10 SQ FT	4.80 SQ FT
MINIMUM FREE AREA	0.19 SQ FT	0.104 SQ FT
WETTED PERIMETER	4.70 FT	10.70 FT
HEAT TRANSFER PERIMETER	4.70 FT	5.90 FT

FABRICATION: PINS RESISTANCE WELDED TO SHELL.
MATERIAL: 18-8 STAINLESS STEEL.
WEIGHT OF UNIT: 13 LBS

FIGURE 31.- HEAT EXCHANGER 4. DESIGNED AND CONSTRUCTED BY HANLON & WILSON CO.

Fig. 31

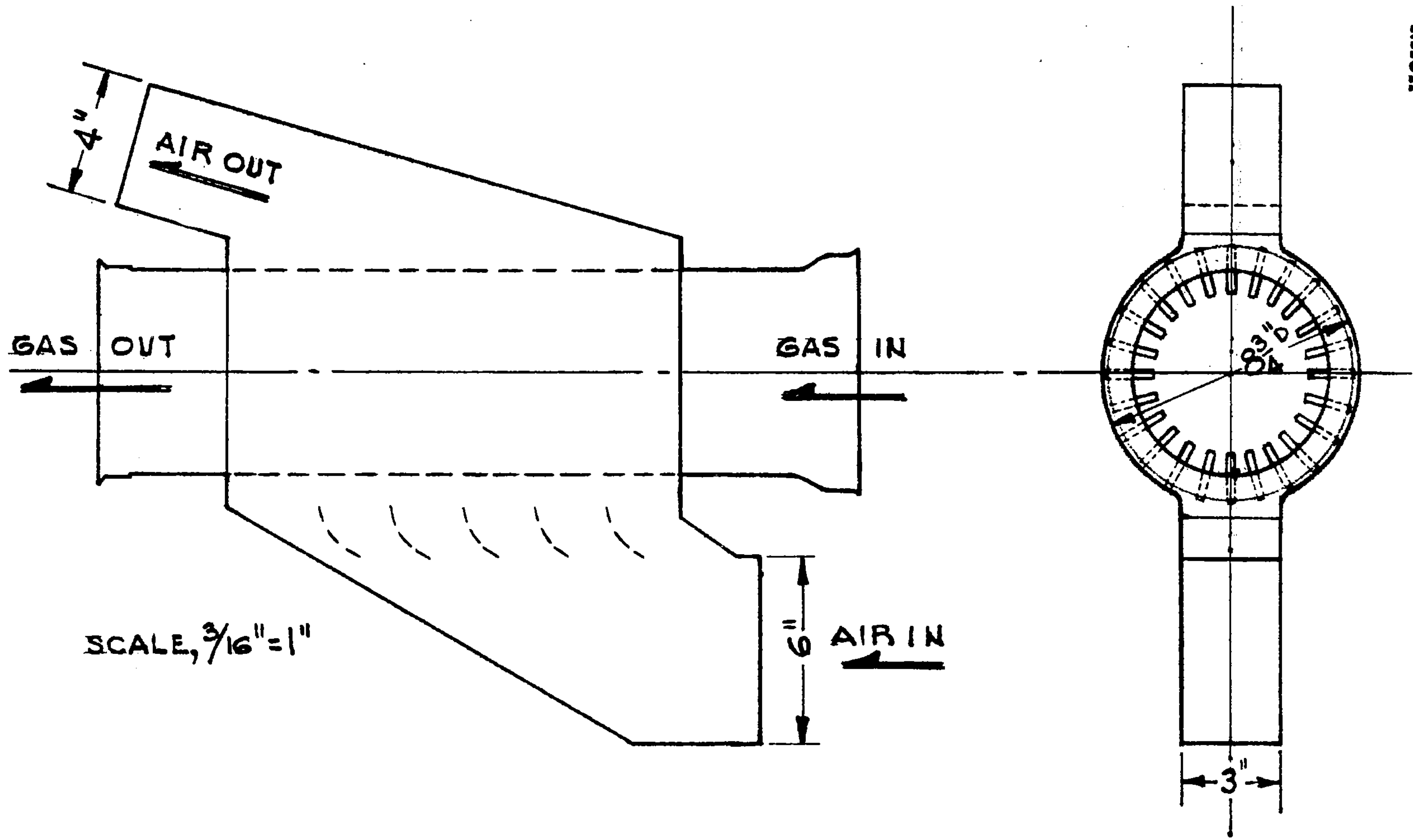


FIGURE 33.-DIAGRAM OF AIR-SIDE SHROUDING USED IN FLIGHT TESTS OF HEAT EXCHANGER 4

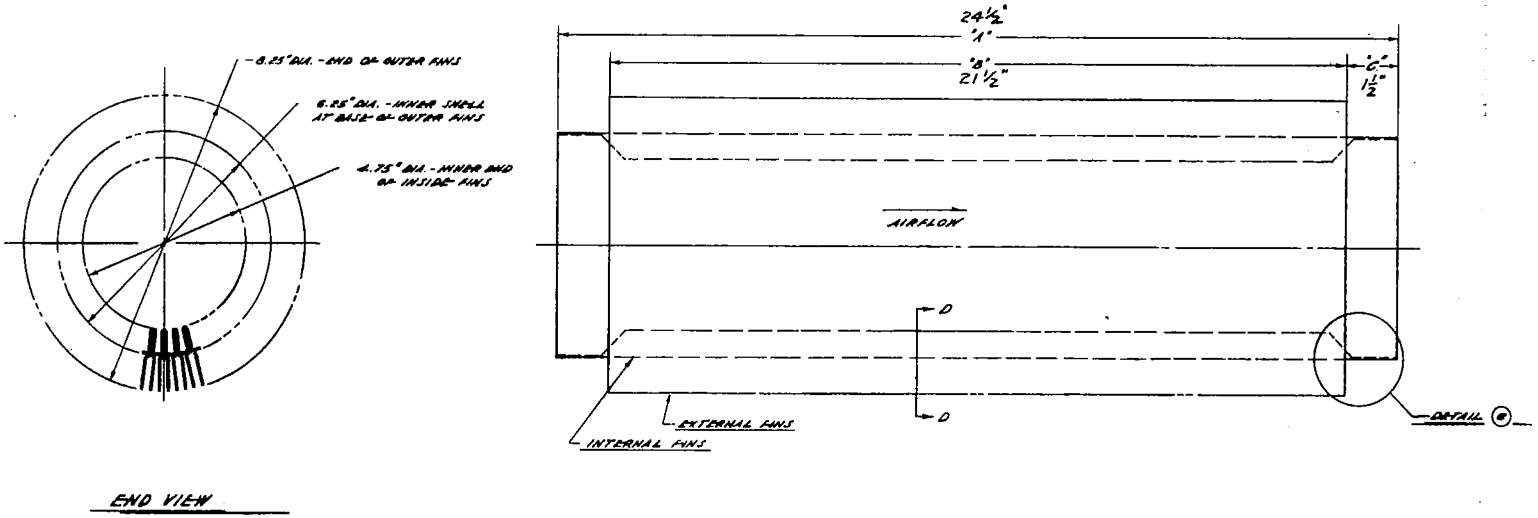
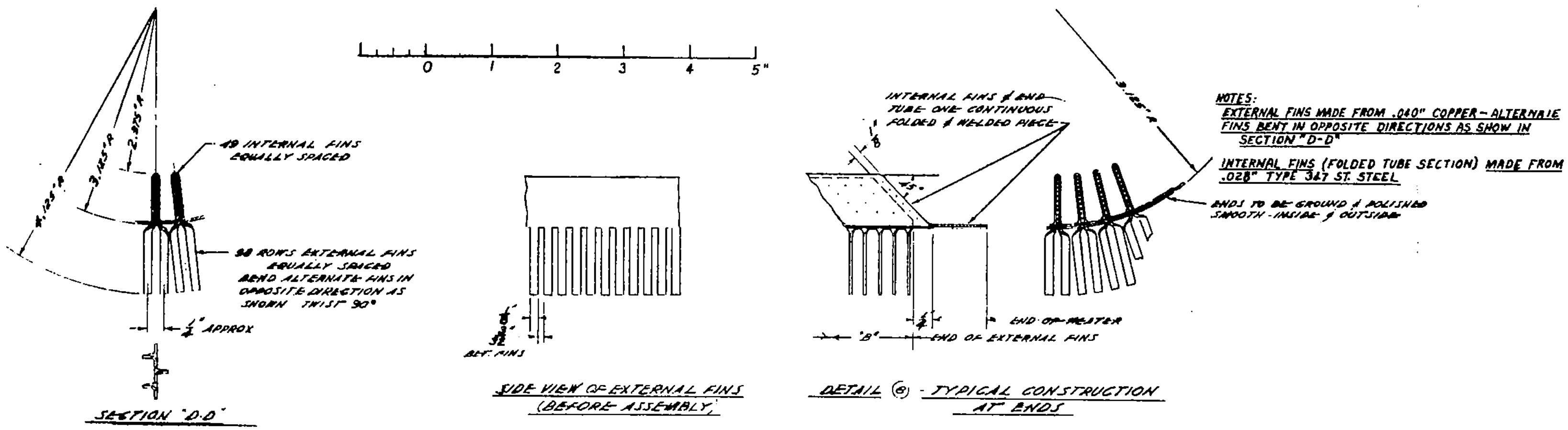


FIGURE 34.- HEAT EXCHANGER 7. DESIGNED AND CONSTRUCTED BY STEWART WARNER CORP.

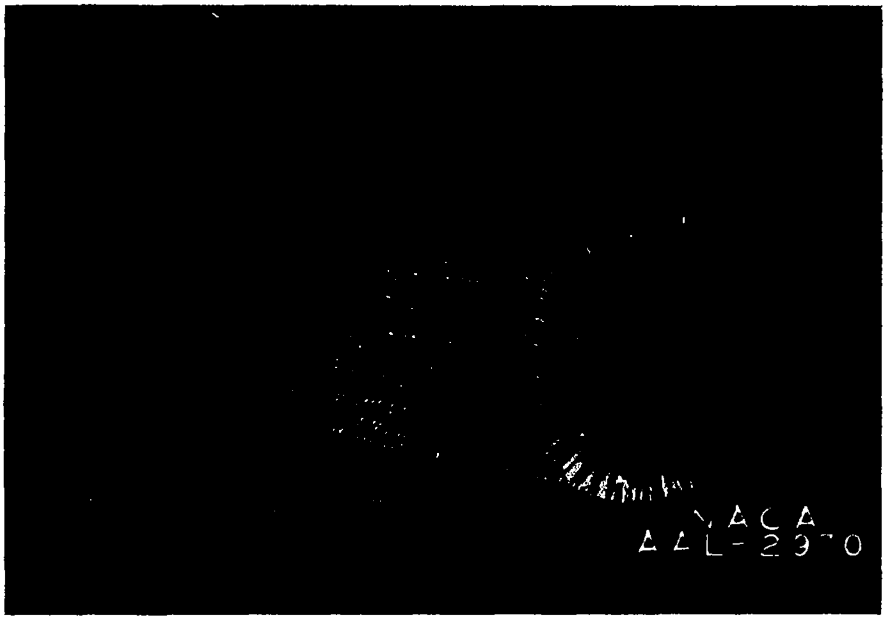


	AIR SIDE	GAS SIDE
HEAT TRANSFER AREA	12.80 SQ FT	13.6 SQ FT
MINIMUM FREE AREA	—	0.18 SQ FT
WETTED PERIMETER	—	0.645 FT
HEAT TRANSFER PERIMETER	—	0.645 FT

FABRICATION - COPPER FINS FURNACE BRAZED TO SHELL. SHELL FORMED OF FOLDED AND SPOT-WELDED STAINLESS STEEL FINS

MATERIALS - COPPER EXTERNAL FINS & .028 TYPE 347 STAINLESS STEEL INNER FINS.

WEIGHT OF UNIT 39 LBS



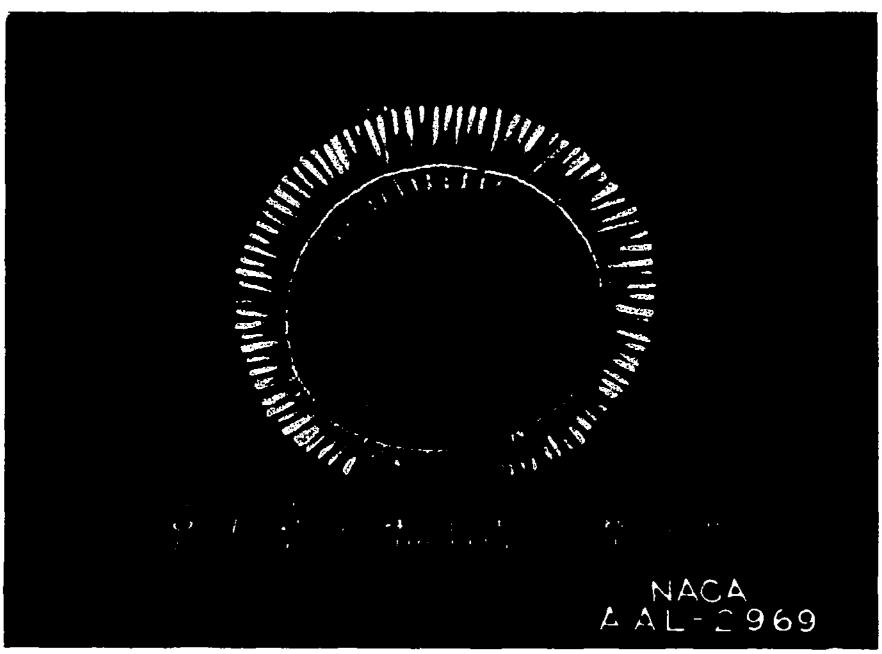


Figure 35.- Heat exchanger 7.

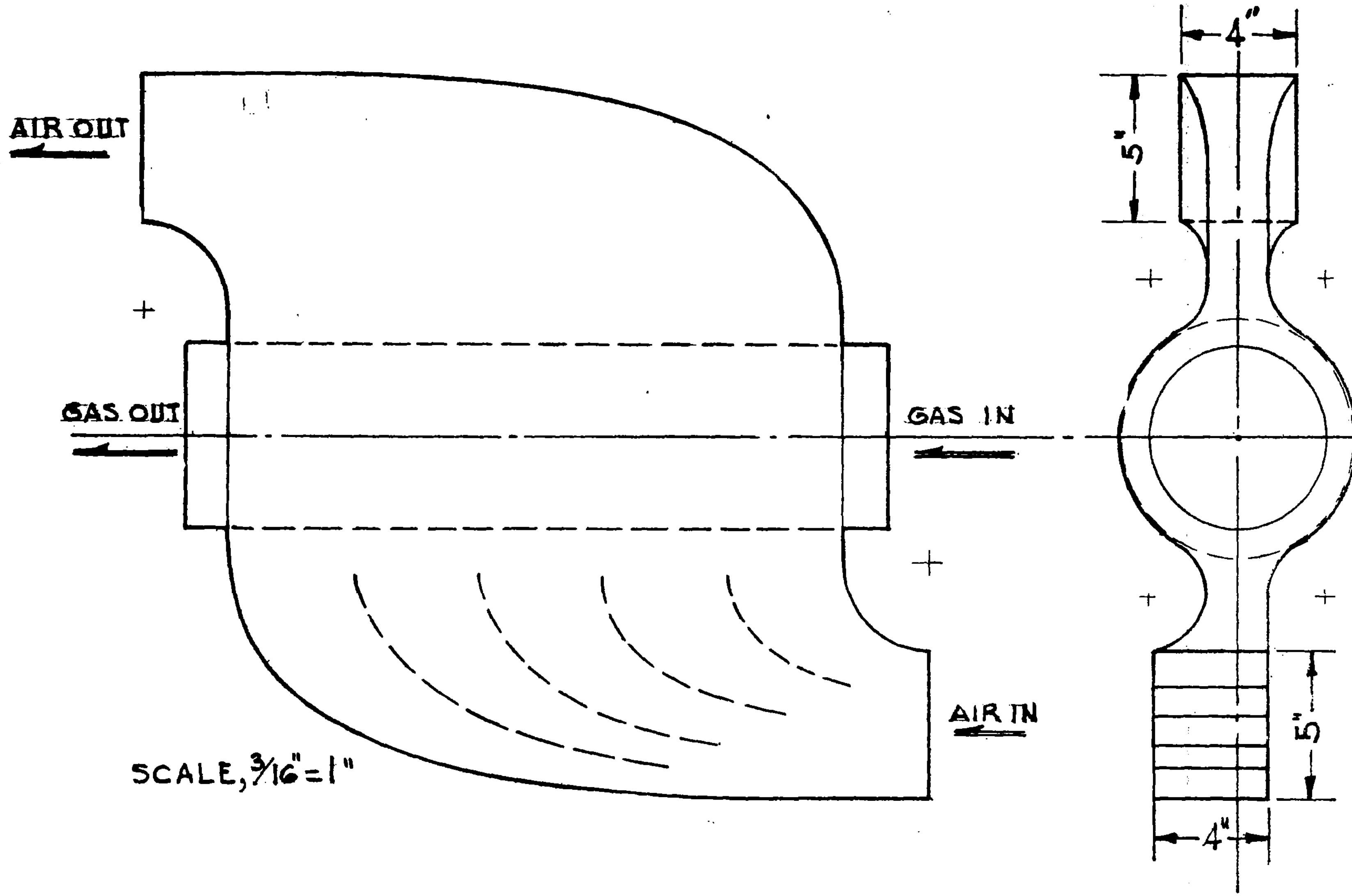


FIGURE 36.- DIAGRAM OF AIR-SIDE SHROUDING USED IN FLIGHT TESTS OF HEAT EXCHANGER 7

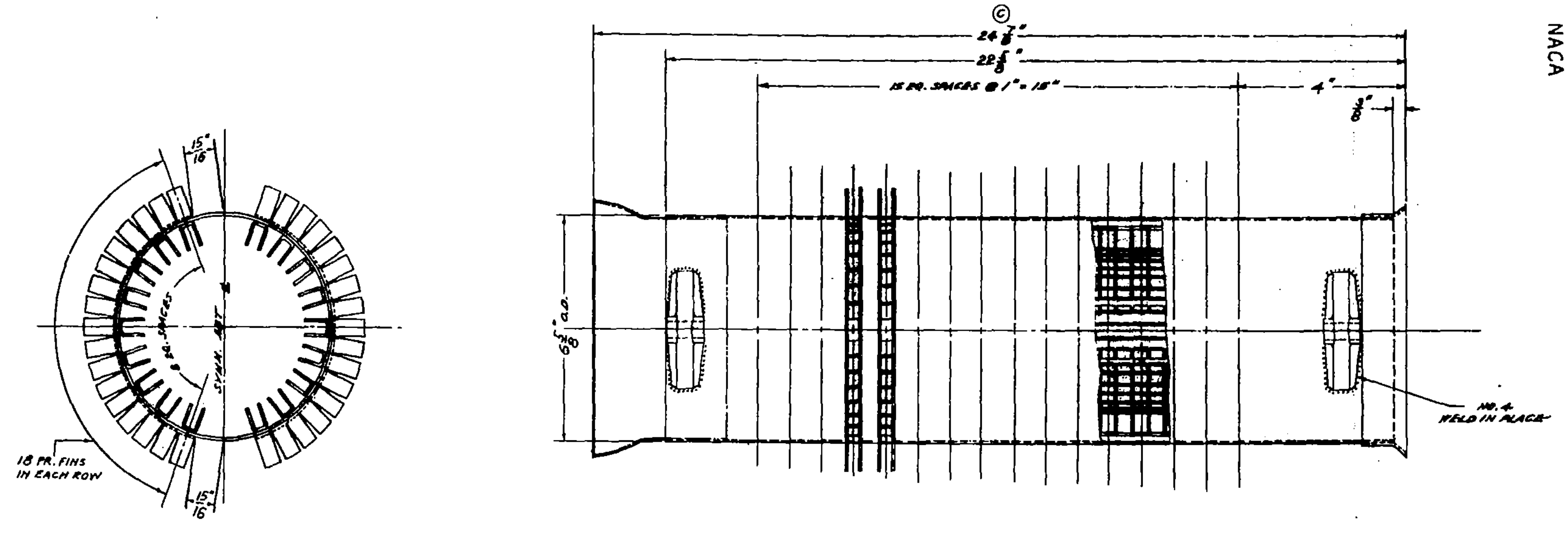
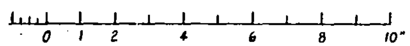
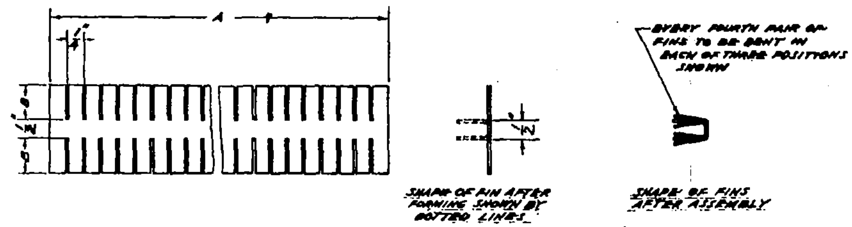


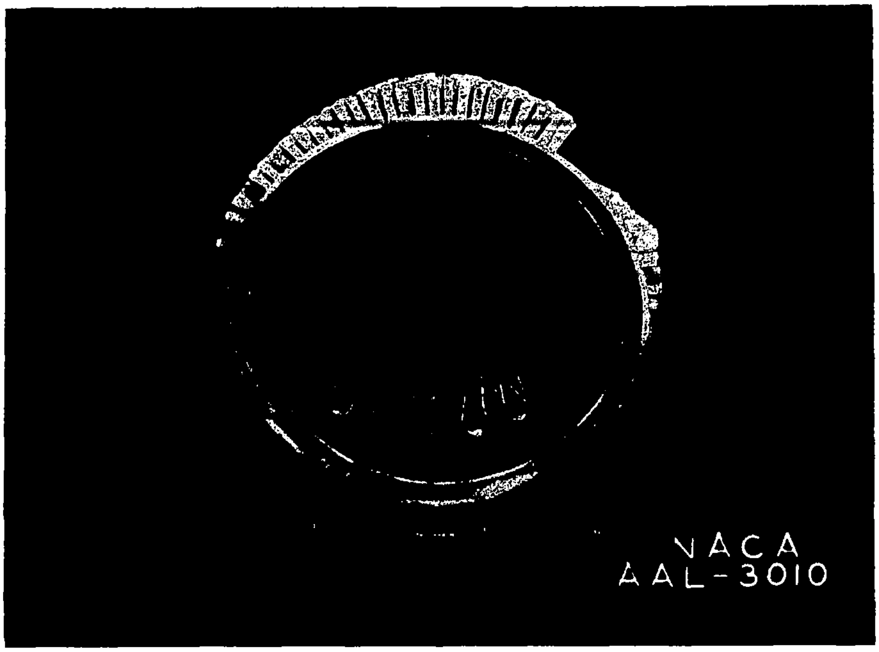
FIGURE 37. HEAT EXCHANGER 28. DESIGNED AT AAL AND CONSTRUCTED BY HANLON & WILSON CO.





	AIR SIDE	GAS SIDE
HEAT TRANSFER AREA	10.0 SQ FT	8.30 SQ FT
MINIMUM FREE AREA	0.22 FT²	0.22 SQ FT
WETTED PERIMETER	16.70 FT	6.20 FT
HEATED TRANSFER PERIMETER	13.50 FT	6.20 FT

FABRICATION – FINS SPOTWELDED TO SHELL
MATERIALS – 0.05 STAINLESS STEEL
WEIGHT OF UNIT – 24.5 LBS



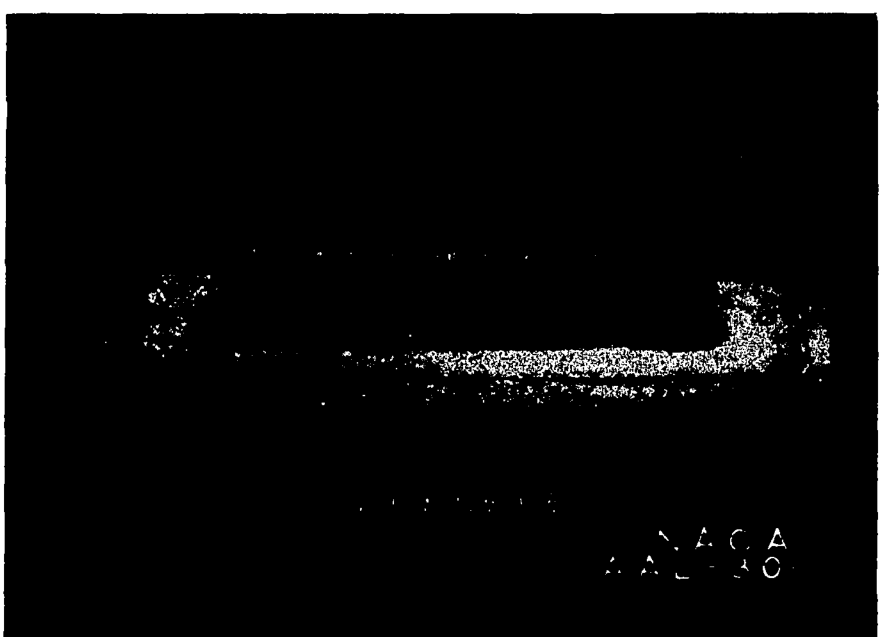


Figure 38.- Heat exchanger 28.

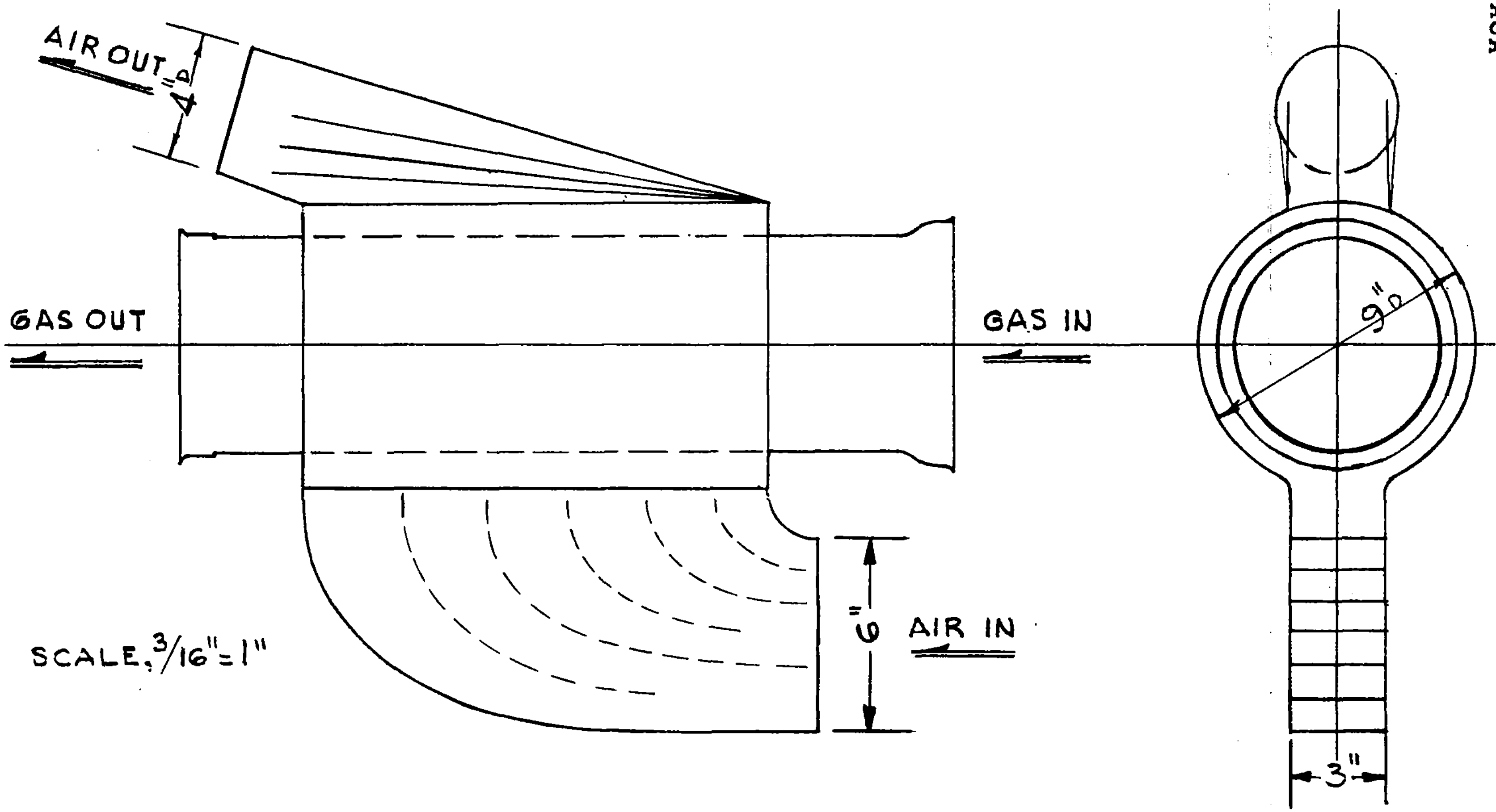
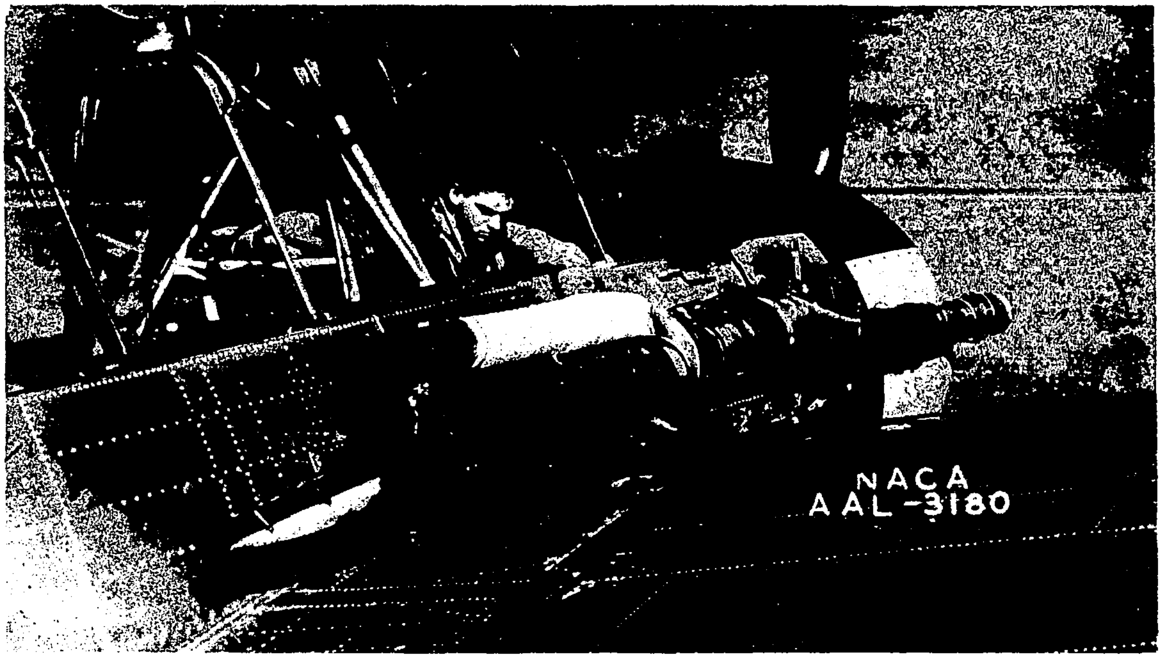


FIGURE 39.-DIAGRAM OF AIR-SIDE SHROUDING USED IN FLIGHT TESTS OF HEAT EXCHANGER 28



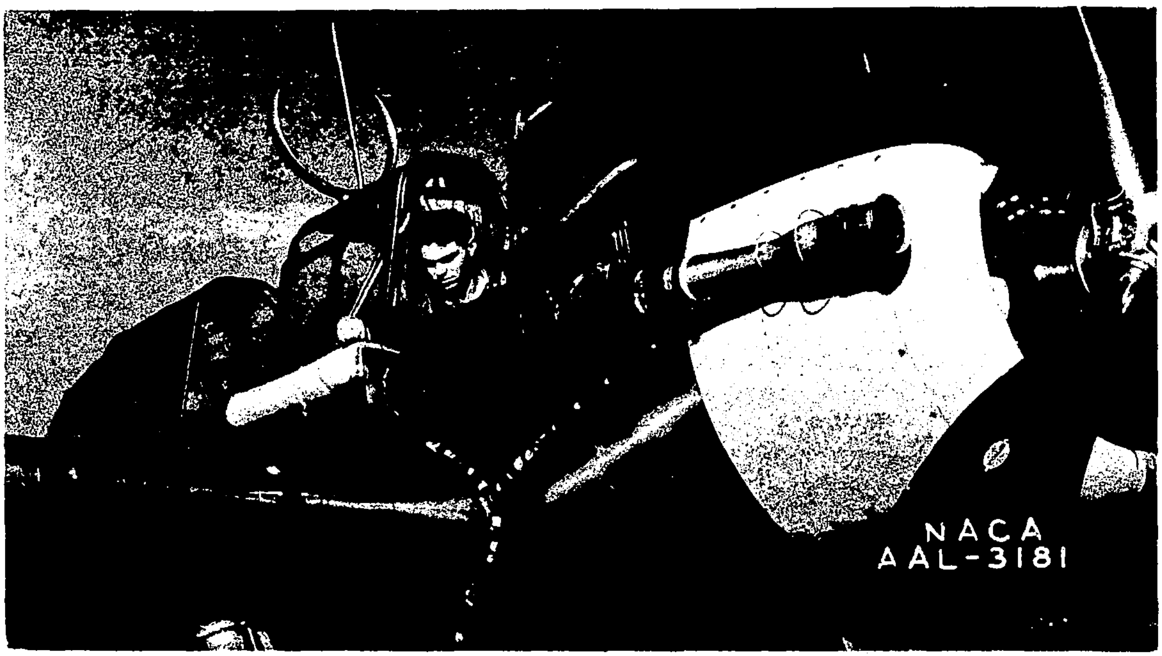


Figure 40.- Typical installation of fluted heat exchanger on a North American O-47A airplane.

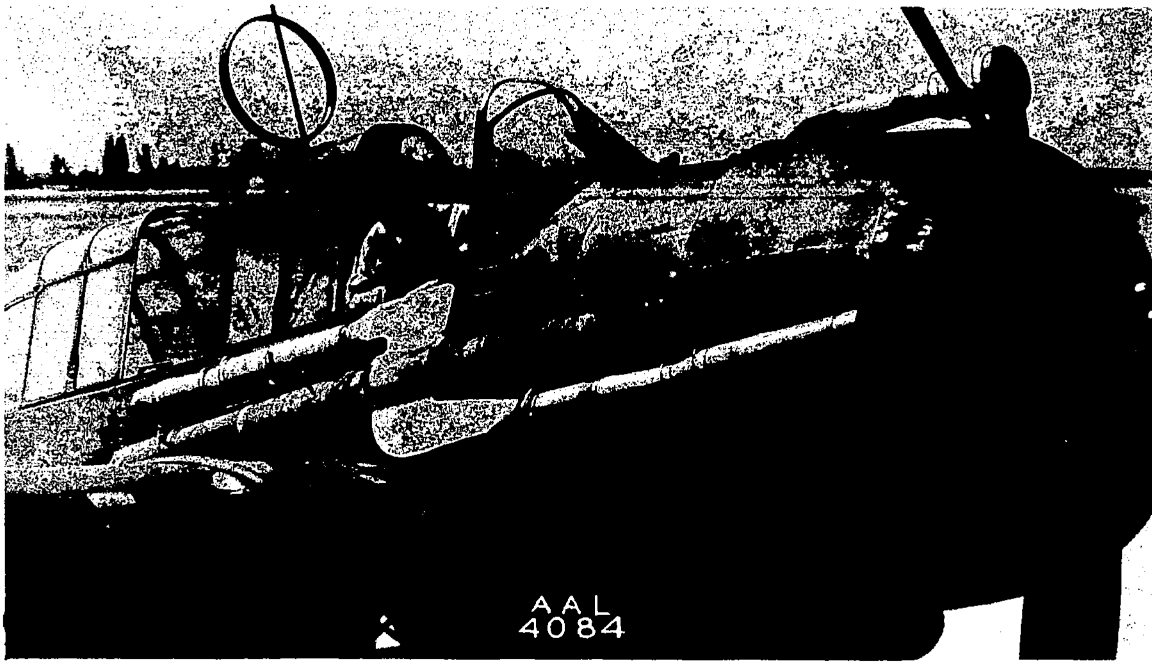
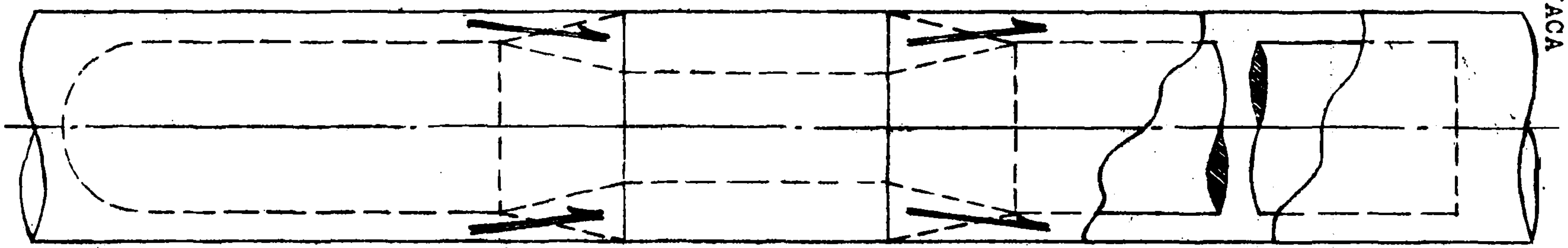
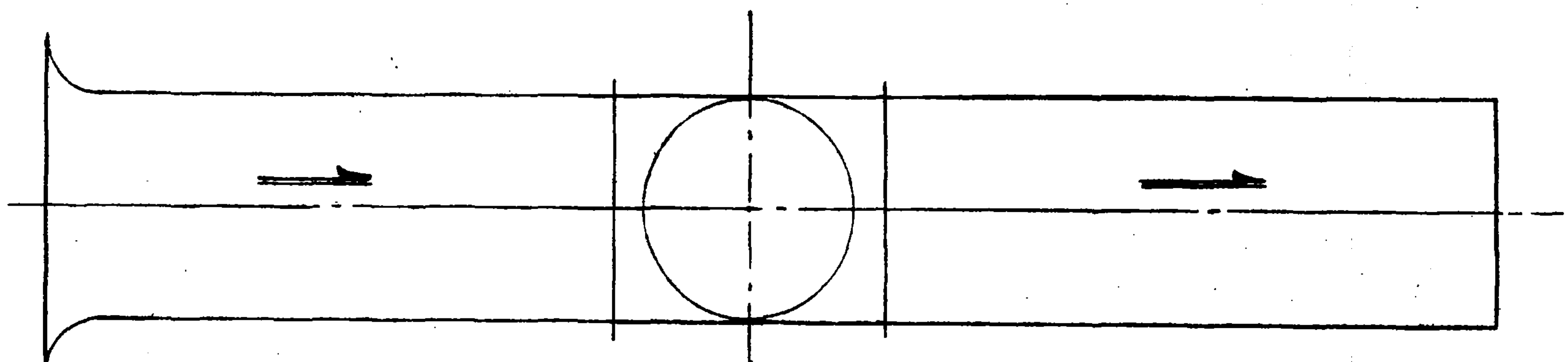


Figure 41.- Typical installation of cross-flow heat exchanger on a North American O-47A airplane.

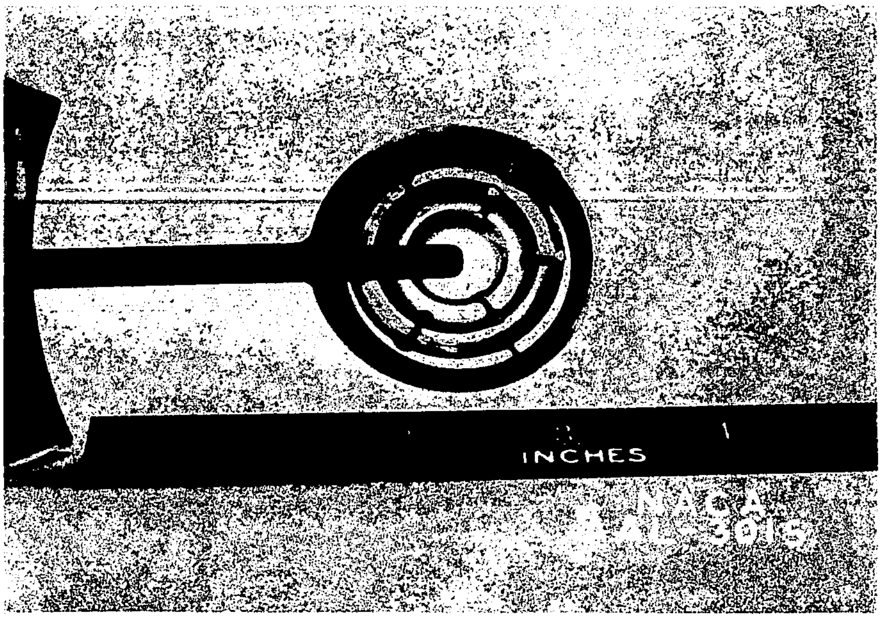


PARALLEL - FLOW



CROSS-FLOW

FIGURE 42.- DIAGRAM SHOWING TYPICAL STRAIGHT SHROUDING USED IN ISOTHERMAL TESTS OF PARALLEL-FLOW AND CROSS-FLOW HEAT EXCHANGERS.



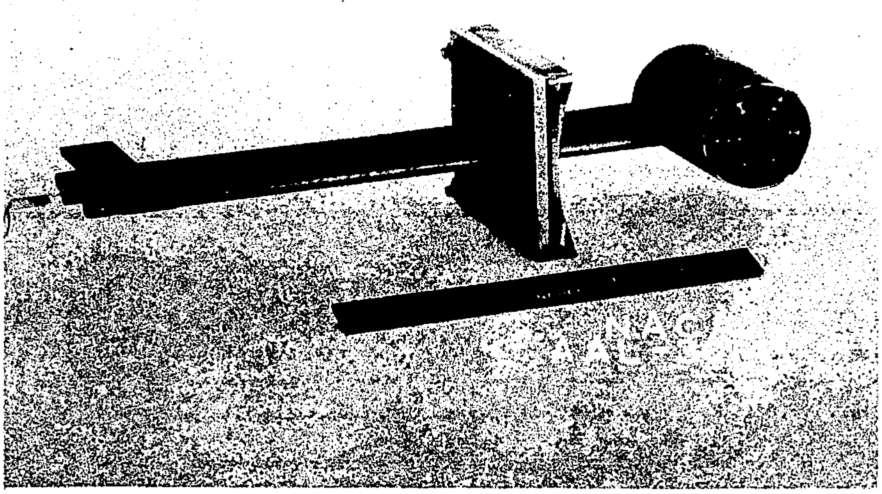


Figure 43.- Quadruple-shielded thermocouple used to measure exhaust-gas temperature.

(1 block = 10 divisions on 1/30" Engr. scale)

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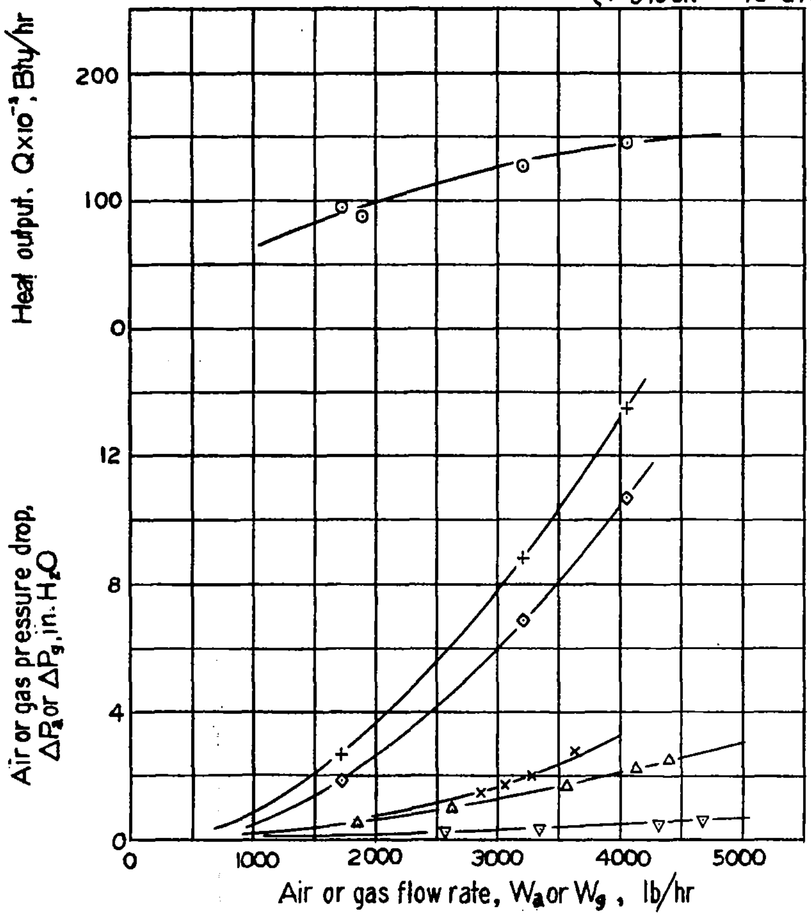
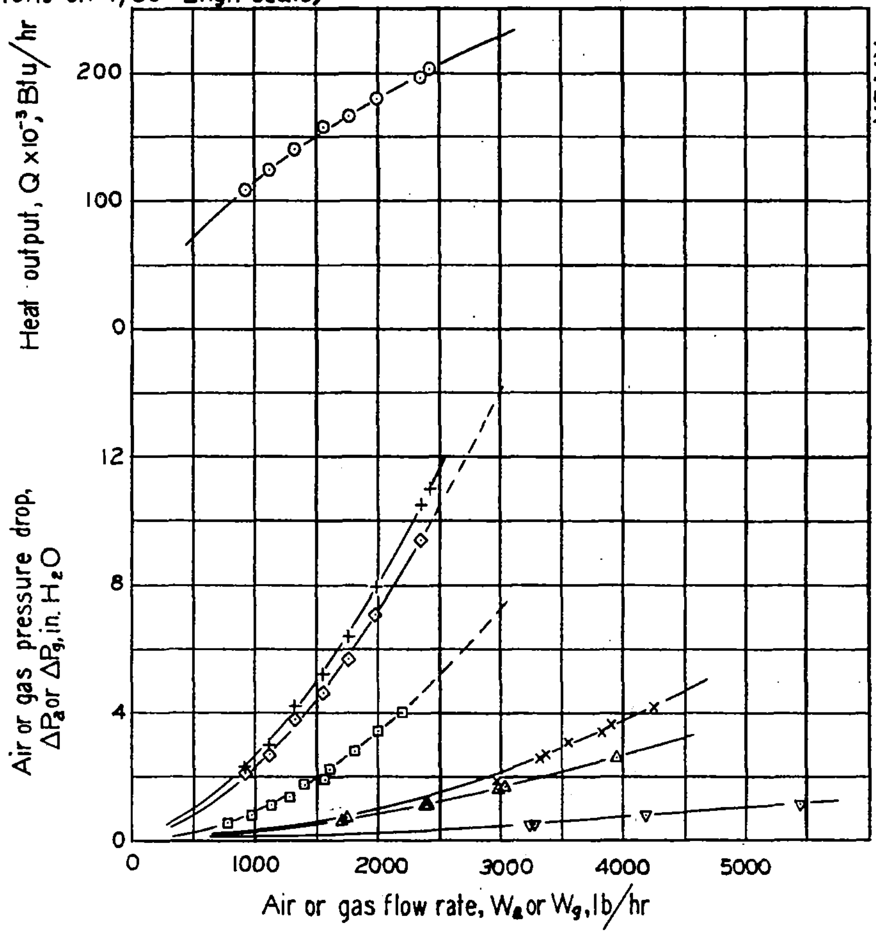


○ Heat output
+ Non-isothermal air static ΔP
◇ Non-isothermal air friction ΔP } t_{ai} = 60°F, t_{gi} = 1600°F, W_g = 3300 lb/hr, press alt = 5000 ft

× Non-isothermal gas static ΔP, t_{gi} = 1600°F, press alt = 5000 ft

△ Isothermal air ΔP with straight shrouding
▽ Isothermal gas ΔP with straight shrouding } t_a = 70°F, Bar = 30.1 in. Hg

Figure.- 44 Performance data, heat exchanger 10.



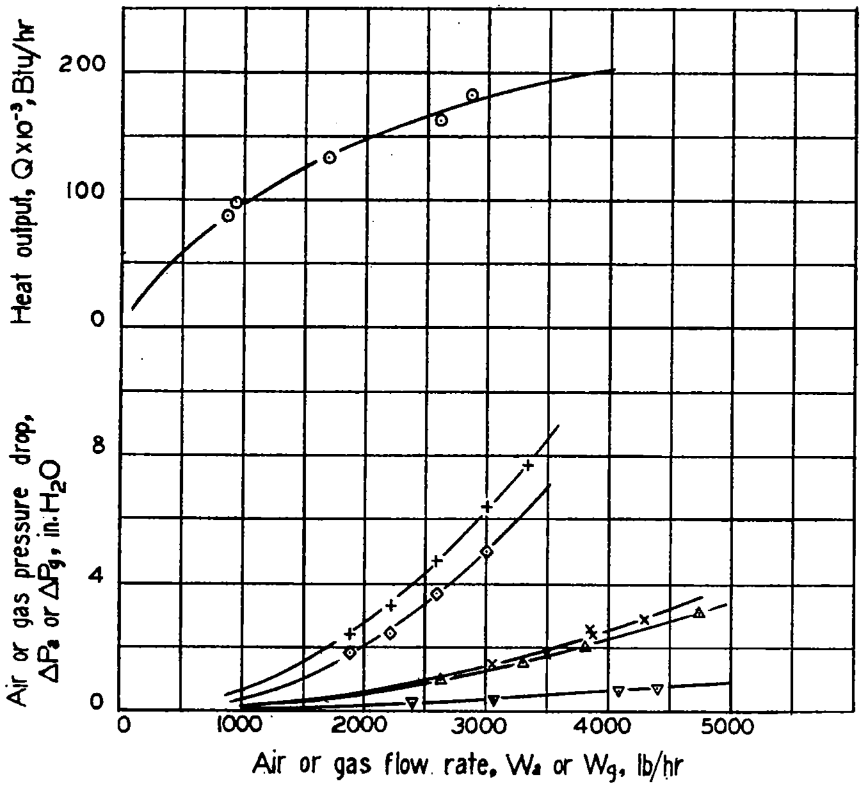
○ Heat output
+ Non-isothermal air static ΔP
◇ Non-isothermal air friction ΔP } t_{ai} = 40°F, t_{gi} = 1600°F, W_g = 3300 lb/hr, press alt = 5000 ft

× Non-isothermal gas static ΔP, t_{gi} = 1600°F, press alt = 5000 ft

□ Isothermal air ΔP with flight shrouding, t_a = 70°F
△ Isothermal air ΔP with straight shrouding, t_a = 85°F
▽ Isothermal gas ΔP with straight shrouding, t_a = 75°F } Bar = 30.2 in. Hg

Figure 45.- Performance data, heat exchanger 12.

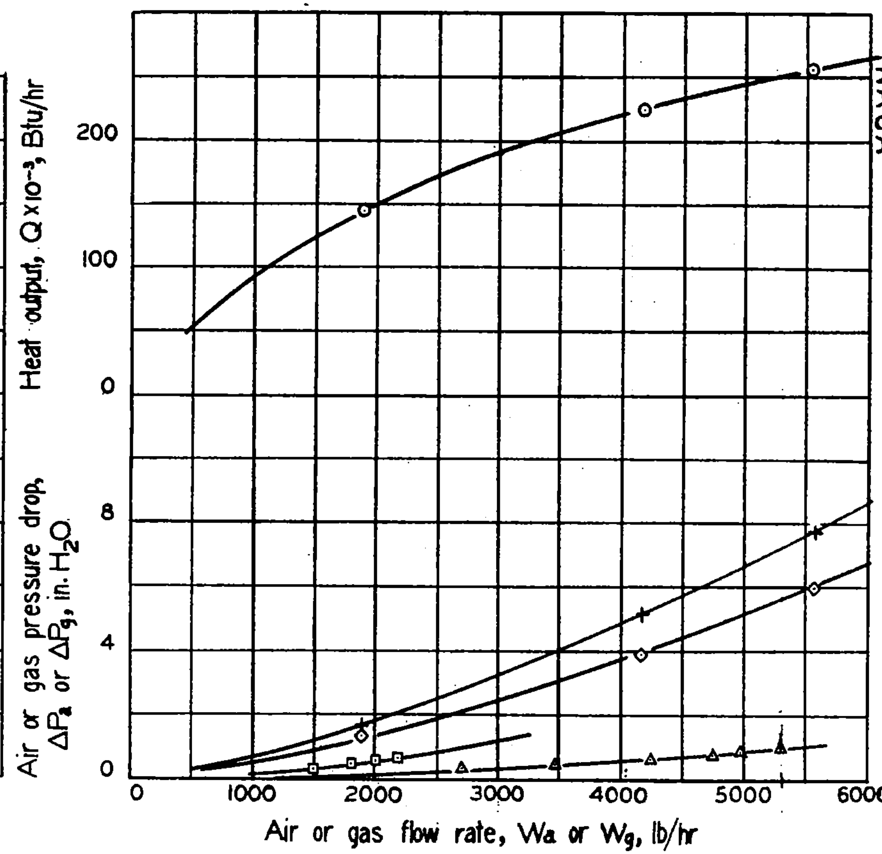
Figs. 44, 45



- ○ Heat output.
- + Non-isothermal air static ΔP
- ◇ Non-isothermal air friction ΔP

} t_{a_1} = 55°F, t_{g_1} = 1600°F, W_g = 3300 lb/hr, press. alt. = 5000 ft

- × Non-isothermal gas static ΔP, t_{g_1} = 1600°F, press alt = 5000 ft
- △ Isothermal air ΔP with straight shrouding, t_a = 70°F, Bar = 30 in. Hg
- ▽ Isothermal gas ΔP with straight shrouding, t_a = 80°F, Bar = 30 in. Hg



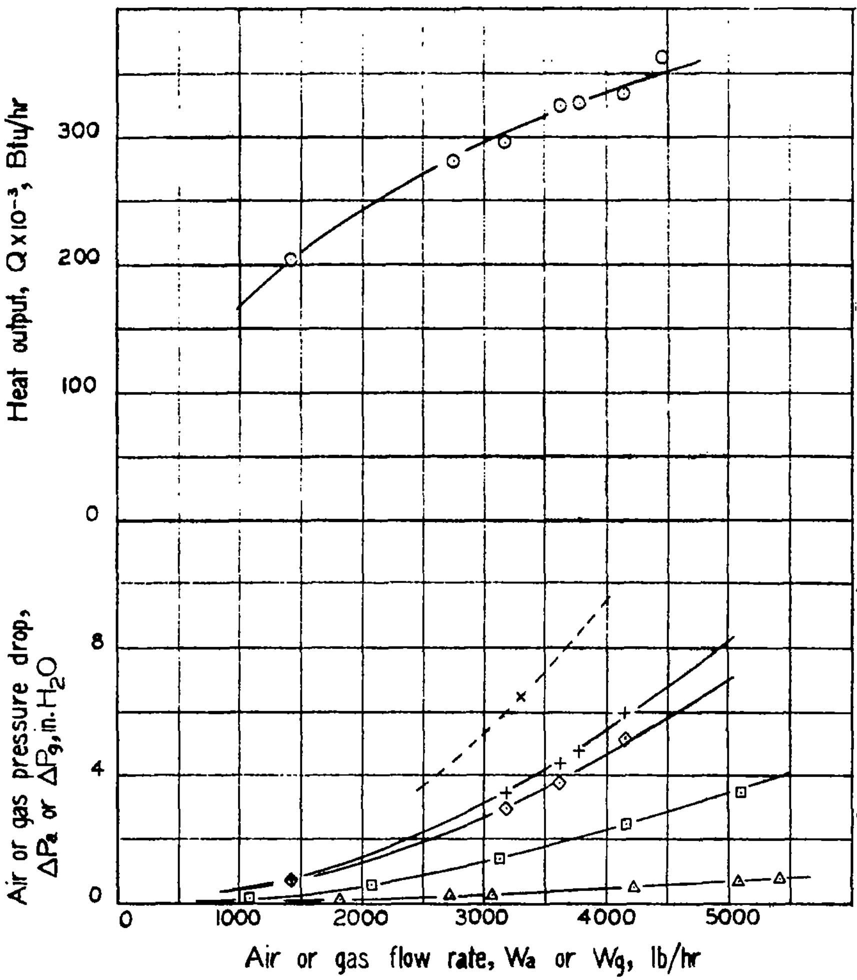
- ○ Heat output
- + Non-isothermal air static ΔP
- ◇ Non-isothermal air friction ΔP

} t_{a_1} = 50°F, t_{g_1} = 1600°F, W_g = 3300 lb/hr, press alt = 5000 ft

- □ Isothermal air ΔP with flight shrouding, t_a = 65°F, Bar = 29.9 in. Hg
- △ Isothermal air ΔP with straight shrouding, t_a = 85°F, Bar = 29.9 in. Hg

Figure 46.- Performance data, heat exchanger 29. (1 block = 10/30")

Figure 47.- Performance data, heat exchanger 35.

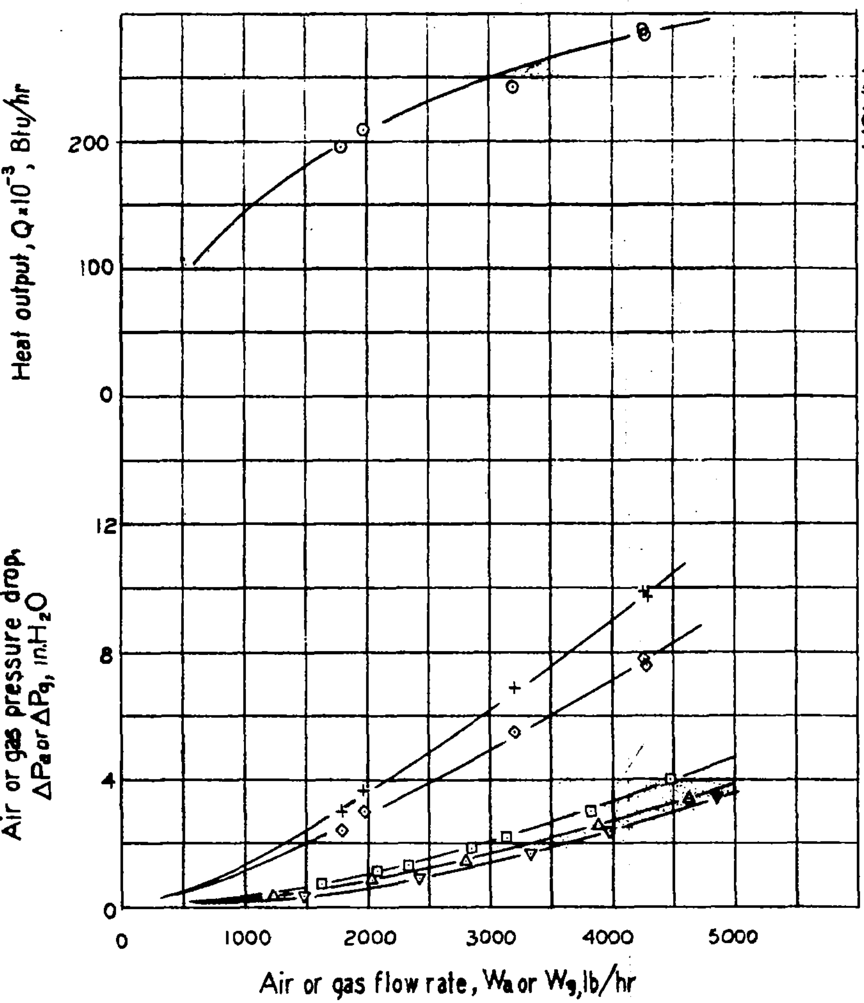


- ○ Heat output
- + Non-isothermal air static ΔP
- ◇ Non-isothermal air friction ΔP

} t_{a_1} = 55°F, t_{g_1} = 1600°F, W_g = 3300 lb/hr, press alt = 5000 ft.

- × Non-isothermal gas static ΔP, t_{g_1} = 1600°F, press alt = 5000 ft
- □ Isothermal air ΔP with flight shrouding, t_a = 70°F, Bar = 30 in. Hg
- △ Isothermal air ΔP with straight shrouding, t_a = 70°F, Bar = 30.1 in. Hg

Figure 48. - Performance data, heat exchanger 48.
(1 block = 10/30")



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- ○ Heat output
- + Non-isothermal air static ΔP
- ◇ Non-isothermal air friction ΔP

} t_{a_1} = 65°F, t_{g_1} = 1600°F, W_g = 3300 lb/hr, press alt = 5000 ft

- × Non-isothermal gas static ΔP, t_{g_1} = 1600°F, press alt = 5000 ft
- □ Isothermal air ΔP with flight shrouding, t_a = 70°F
- △ Isothermal air ΔP with straight shrouding, t_a = 60°F
- ▽ Isothermal gas ΔP with straight shrouding, t_a = 80°F

} Bar = 30.1 in. Hg

Figure 49. - Performance data, heat exchanger 11.

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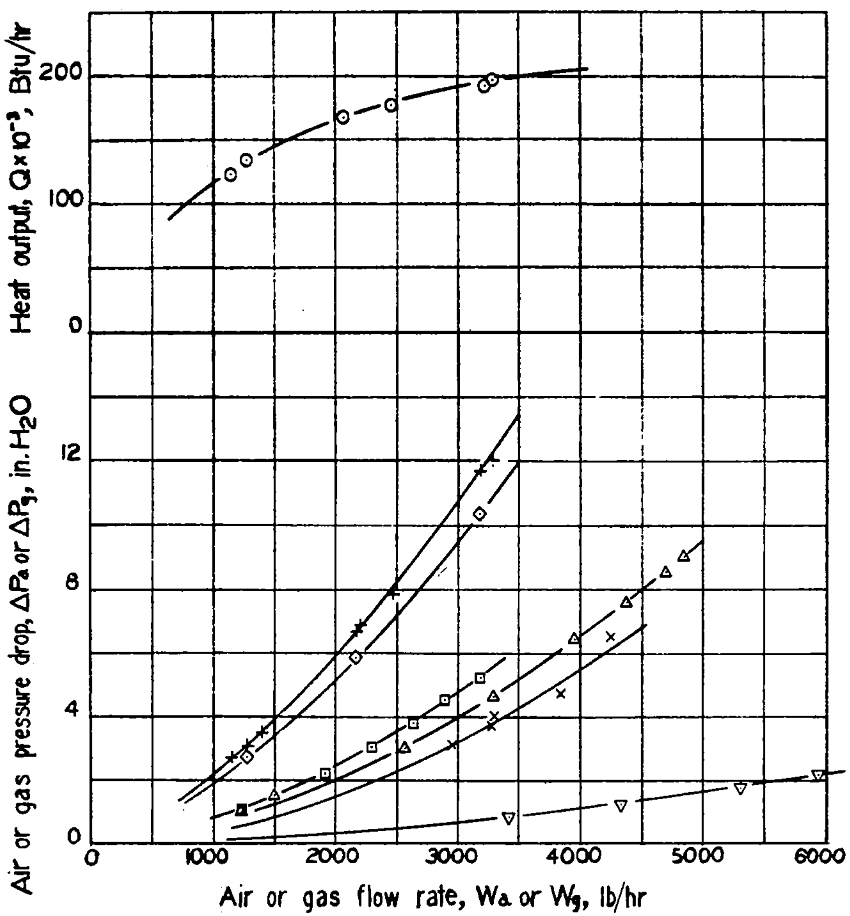


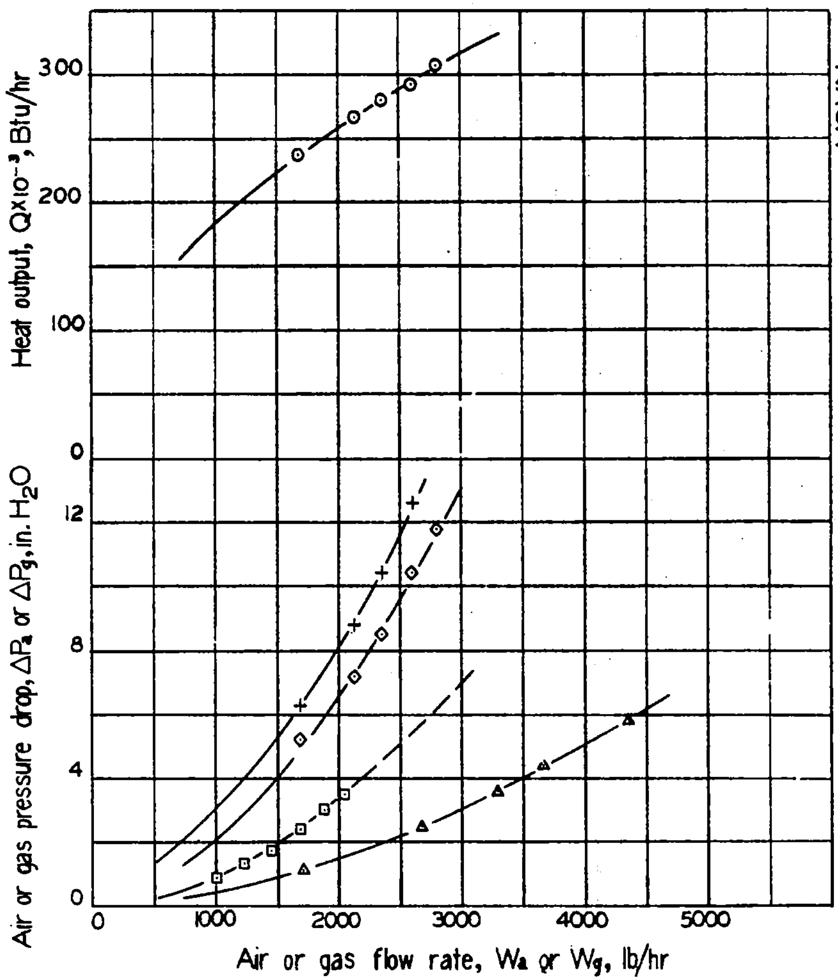
○ Heat output
+ Non-isothermal air static ΔP
◇ Non-isothermal air friction ΔP
} t_{a_1}=60°F, t_{g_1}=1600°F, W_a=3300 lb/hr, press alt = 5000 ft

× Non-isothermal gas static ΔP, t_{g_1}=1600°F, press alt = 5000 ft

□ Isothermal air ΔP with flight shrouding
▽ Isothermal gas ΔP with straight shrouding
} t_a= 80°F, Bar = 30 in. Hg

△ Isothermal air ΔP with straight shrouding, t_a=65°F, Bar.=30.8 in. Hg

Figure 50.-Performance data, heat exchanger 42. (1 block=10/30")



○ Heat output
+ Non-isothermal air static ΔP
◇ Non-isothermal air friction ΔP
} t_{a_1}-50°F, t_{g_1}-1600°F, W_g-3300 lb/hr, press alt = 5000 ft

□ Isothermal air ΔP with flight shrouding, t_a=65°F, Bar=30.5 in. Hg
△ Isothermal air ΔP with straight shrouding, t_a=70°F, Bar=30.1 in. Hg

Figure 51.-Performance data, heat exchanger 34.

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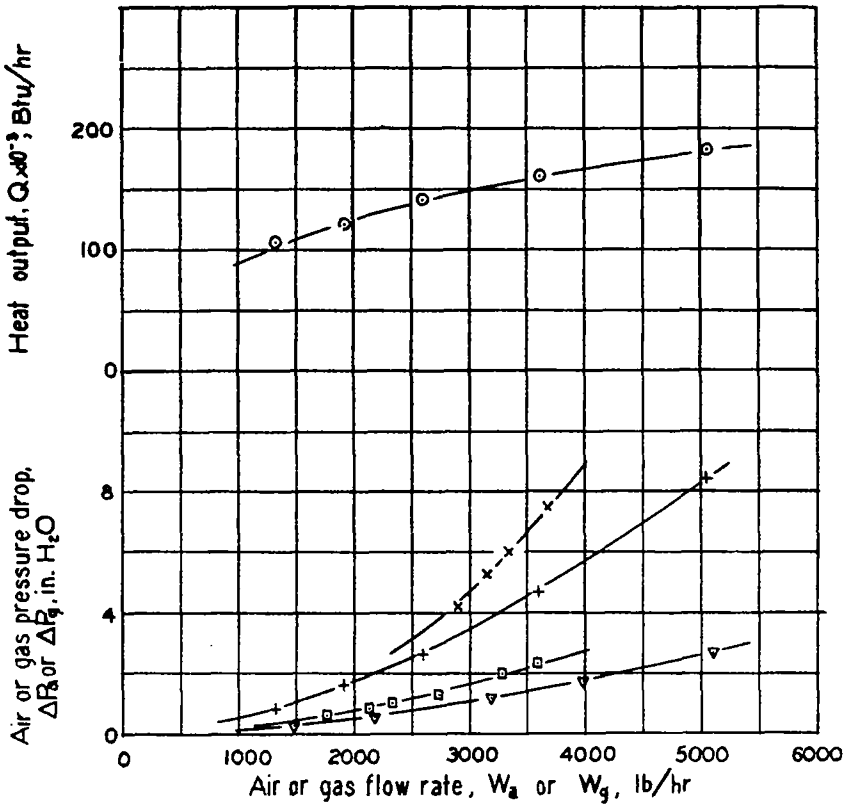
Figs. 50,51



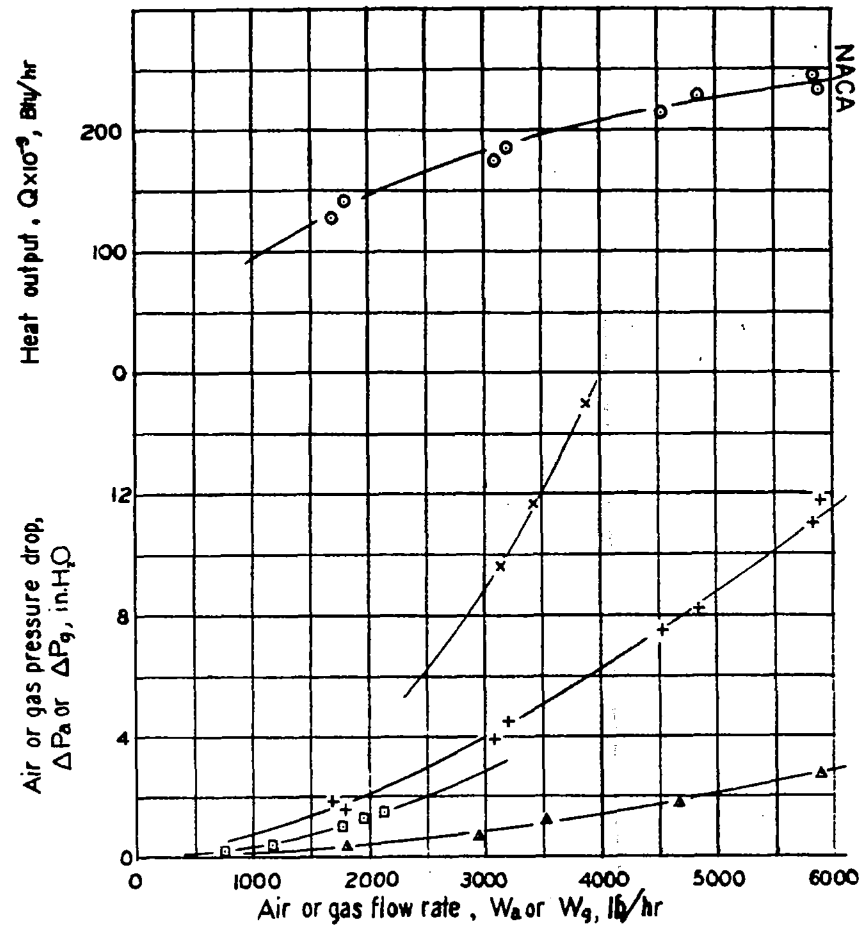
o Heat output
\+ Non-isothermal air static ΔP

} t_{a_i} = 45°F, t_{g_i} = 1600°F
W_g = 3300 lb/hr
press alt = 5000 ft

× Non-isothermal gas static ΔP, t_{g_i} = 1600°F, press alt = 5000 ft
□ Isothermal air ΔP with flight shrouding, t_a = 60°F, Bar = 30.3 in.Hg
▽ Isothermal gas ΔP with straight shrouding, t_a = 82°F, Bar = 30.8 in.Hg

Figure 52.– Performance data, heat exchanger 39.

(1 block = 10/30")



o Heat output
\+ Non-isothermal air static ΔP

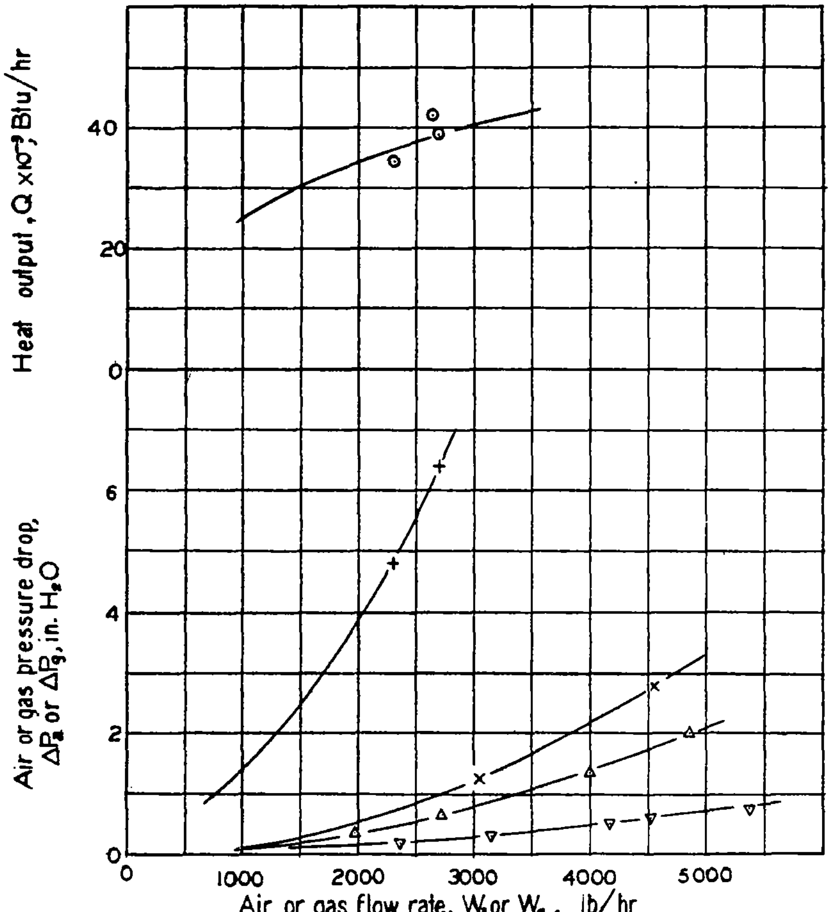
} t_a = 50°F, t_{g_i} = 1600°F
W_g = 3300 lb/hr
press alt = 5000 ft

× Non-isothermal gas static ΔP, t_{g_i} = 1600°F, press alt 5000 ft
□ Isothermal air ΔP with straight shrouding
△ Isothermal air ΔP with flight shrouding

} t_a = 65°F
Bar = 30.1 in.Hg

Figure 53.–Performance data heat exchanger 40.

Figs. 52,53

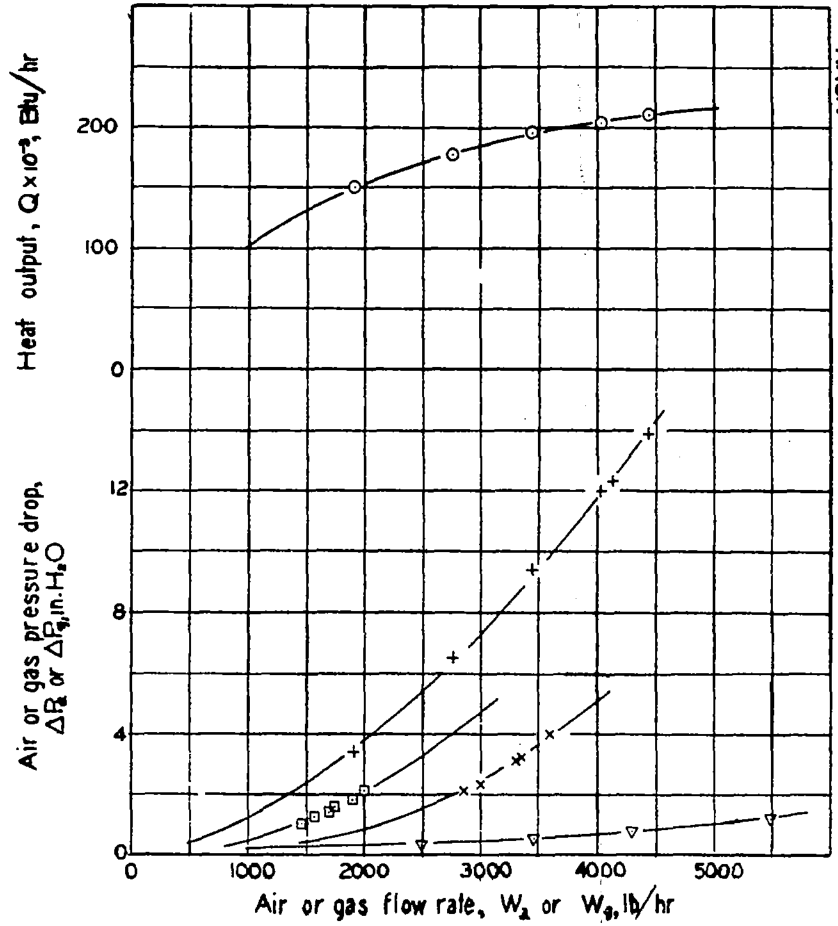


○ Heat output
\+ Non-isothermal air static ΔP } t_{a_i} = 85°F, t_{g_i} = 1600°F, W_g = 3300 lb/hr, press alt - 5000 ft

× Non-isothermal gas static ΔP, t_{g_i} = 1600°F, press alt = 5000 ft
△ Isothermal air ΔP with straight shrouding, t_a = 65°F, Bar = 30.2 in. Hg
▽ Isothermal gas ΔP with straight shrouding, t_a = 75°F, Bar = 29.95 in. Hg

Figure 54.– Performance data, heat exchanger 4.

(1 block = 10/30")



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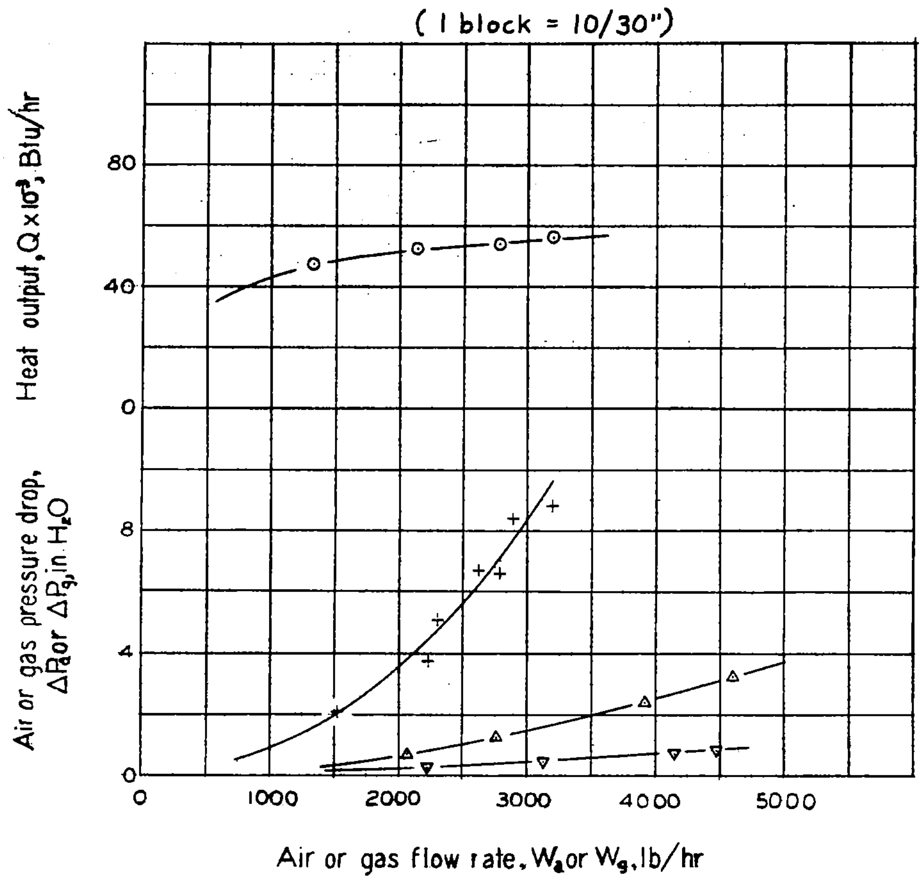
○ Heat output
\+ Non-isothermal air static ΔP } t_{a_i} = 50°F, t_{g_i} = 1600°F, W_g = 3300 lb/hr, press alt = 5000 ft.

× Non-isothermal gas static ΔP, t_{g_i} 1600°F, press alt - 5000 ft.
□ Isothermal air ΔP with flight shrouding, t_a = 65°F
▽ Isothermal gas ΔP with straight shrouding, t_a = 80°F } Bar = 30.0 in. Hg

Figure 55.– Performance data, heat exchanger 7.

Figs. 54, 55



○ Heat output
+ Non-isothermal air static ΔP

t_{a_i} = 60°F , t_{g_i} = 1600°F
W_g = 3300 lb/hr
press alt - 5000 ft

△ Isothermal air ΔP with straight shrouding, t_a = 65°F
▽ Isothermal gas ΔP with straight shrouding, t_a = 80°F

Bar = 30.0 in. Hg

Figure 56.– Performance data, heat exchanger 28.